SAND85-0045
Unlimited Release
May 1985

# AN ANALYSIS OF DRAG REDUCING AGENTS FOR USE AT THE STRATEGIC PETROLEUM RESERVE SITE AT WEST HACKRERRY, LOUISIANA

by

Thomas E. Hinkebein
SPR Geotechnical Division
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

An analysis method for evaluating the use of polymeric drag reducing agents (DRA) within the Strategic Petroleum Reserve brine disposal pipelines has been formulated. This method is based upon a detailed flow model describing the flow of solutions with DRA through the brine pipeline at West Hackberry, Louisiana. The verification of this model is confirmed by the Southwest Research Laboratory data. This model indicates that the drag reduction effect is dependant on polymer solution type and concentration as well as the fluid wall shear stress and the pipe roughness. For the West Hackberry pipeline, it is projected that a 20 percent flow increase is attainable with the best polymers. Further drag reducing agent tests are proposed to allow a more accurate prediction of flow improvement.

## ACKNOWLEDGMENT

The author wishes to acknowledge the support of the following people: T. S. Ortiz, 6312,. for setting up the original investigation of drag reducing agents at **SwRI** and R.R. Beasley, 6257, for his assistance in defining polymer concentrations to be used in the **SwRI** tests.

## EXECUTIVE SUMMARY

The addition of drag reducing agents to the brine flowing through the disposal pipeline at the West Hackberry, Louisiana SPR site is being considered as a means to significantly increase the fluid flow rate. When drag reducing polymers were added to a synthetic brine, data obtained at Southwest Research Institute revealed significant increases in the flow through a laboratory piping network. A relationship between Reynolds number and friction factor has been developed which describes this polymeric flow and important parameters have been determined for each polymer. A numerical fluid flow model which employs this polymeric Reynolds number versus friction factor relationship has been applied to the piping network used for brine disposal at West Hackberry. This analysis reveals that significant flow increases are projected upon the addition of polymer. Flow tests are planned at West Hackberry to further determine the effect of low concentration of polymer, of field brines, and of pipeline diameter on the fluid flow of these solutions.

Fluid flow in the West Hackberry brine disposal pipeline is highly turbulent. Turbulent flow is known to have a central core of almost uniform velocity and a boundary layer next to the wall where the flow is assumed to be laminar. Turbulence arises at the edge of the boundary layer and propagates into the free stream. When high molecular weight polymers are added to the solution, the linear molecules interfere with the turbulence formation process. As a consequence the level of turbulence near the wall is reduced and less energy is lost to turbulent processes.

Experiments to screen the performance of 30 drag reducing polymers were performed at Southwest Research Institute. These experiments were performed in a flow loop consisting of a reservoir tank, pump, and a series arrangement of a L-inch diameter pipe, a 4-inch-diameter pipe, and a Z-inch-diameter pipe. Polymer solution was drawn out of the reservoir tank through the pump and flow loop and then returned to the reservoir. Instrumentation provided flow rate and pressure drop data in each of the three pipe legs continuously. Since the fluid flowed through each of the three legs in series, three different wall shear stress conditions were obtained simultaneously for each

polymer solution. Hence, this flow loop allowed a rapid screening of potential flow reducers. Data were typically gathered at one concentration which reflects the price of the polymer and the cost structure of the pumping and leaching operations.

The particular application for these fluid friction reducing agents, considered in this report, is the West Hackberry brine disposal pipeline. This pipeline is a 36-inch-diameter, 26.4-mile-long pipeline which terminates in a diffuser section in the Gulf of Mexico. The total brine flow varies between 800,000 and 1,000,000 BBL/day while the pressure in the line is limited to 787 psi. Flow in the total pipeline system was numerically simulated. The results of these calculations are that significant flow improvement occurs when the pipeline is very smooth. Increased roughness in the pipelines reduces polymeric flow enhancement. At typical roughness and pipe flow rates, a 20 percent increase in flow is forecast.

A new series of flow tests are defined to address several unanswered questions. These tests represent the final phase of the program, requested by DOE, to evaluate the effectiveness of drag reducing polymers on brine flow. The concentration dependence of the polymer flow is not yet well defined by the current data since a typical experiment investigated one polymer concentration. The shear stability of drag reducing agents must be addressed since the data in this study were obtained in a recirculating flow loop rather than in a single pass apparatus. The actual field brine will also contain divalent ions and undissolved solids which have an unknown effect on the polymer performance. Finally, the laws which allow for scaling to larger pipe diameters (36 inches) must be verified. Consequently, the new flow tests are defined for single-pass pipelines (both 3 and 36 inches). Field brine will be employed and polymer will be added to the flow line downstream of any centrifugal pumps or major flow constrictions. The flow ranges and polymer concentrations will bracket the useful and expected values. Different pipeline diameters will allow scaling laws to be verified. Hence, these new data, in conjunction with the screening data obtained at SwRI, will allow accurate analyses of performance.

**CONTENTS**

LIST OF FIGURES

## List of Figures (Continued)

## LIST OF TABLES

## NOMENCLATURE

| | |
|---|---|
| **A, B** | constants |
| c | polymer concentration |
| D | pipe diameter |
| DRA | Drag Reducing Agents |
| $g_c$ | gravitational constant |
| $g$ | acceleration of gravity |
| L | pipe length |
| MBD | thousands of barrels per day |
| P | pressure |
| v | average velocity |
| $z$ | elevation of pipe |
| $\delta$ | slope of polymeric curve on Prandtl-Karman coordinates |
| c | pipe roughness |
| $\rho$ | fluid density |
| $\sum F$ | fluid friction head loss |
| $\tau$ | wall shear stress |
| $\mu$ | dynamic viscosity |
| v | kinematic viscosity |

<u>Subscripts</u>

| | |
|---|---|
| c | critical wall shear stress |
| e | exit |
| msl | mean sea level |
| P | polymer solution |
| s | solution without polymer (brine) |
| 1 | position 1 |
| 2 | position 2 |
| 3 | position 3 |

<u>Dimensionless Terms</u>

| | |
|---|---|
| f | Fanning friction factor $= \dfrac{g_c D\Delta P}{2\rho v^2 L} = \dfrac{2\tau g_c}{\rho V^2}$ |
| $k^+_{es}$ | maximum dimensionless pipe roughness $= \dfrac{\varepsilon}{\nu}\sqrt{\dfrac{\tau}{\rho}}$ |
| Re | Reynolds Number $= \dfrac{Dv\rho}{\mu}$ |

## A. INTRODUCTION

The leaching of a cavern within the Strategic Petroleum Reserve is a solution mining operation. Approximately seven barrels of brine must be pumped to form one barrel of cavern space. At West Hackberry, Louisiana this brine pumping rate approaches one million barrels per day so that 140,000 BBL of cavern storage is created daily. The use of drag reducing agents, DRA, offers the potential of reducing the brine pumping costs (and consequently leaching costs) or allowing the brine flow rate (and consequently leaching rate) to be significantly increased.

Several limitations currently exist on the maximum pumping rate attainable on site. First, there is a limitation on the head pressure which can be developed in the pipeline. Second, during the early phases of leaching there is a brine residence time requirement in order to allow the brine to become saturated. Third, the Environmental Protection Agency limits the total flow in the brine pipeline to 1.1 MMBBL/day. The use of drag reducing agents offers the possibility of increasing the flow rate within the first limitation.

This report will outline the techniques and methodology used to compare the technical merits of eleven different polymeric materials for use as drag reducing agents.

## B. A MODEL OF THE RELATIONSHIP BETWEEN REYNOLDS NUMBER AND FRICTION FACTOR FOR POLYMERIC SOLUTIONS

Turbulent flow of a Newtonian fluid through a rough pipe is empirically described by

$$\frac{1}{\sqrt{f}} = 4.0 \log \left( \frac{3.72}{\frac{4.67}{Re\sqrt{f}} + \frac{\varepsilon}{D}} \right) \qquad (1)$$

A plot of $1/\sqrt{f}$ versus $Re\sqrt{f}$ is referred to as a Prandtl-Karman (P--K) plot.

A consideration of the effect of adding drag reducing agents to a flowing fluid has been advanced by several investigators.[1, 4, 5, 6, 7, 10, 11, 12] They report that turbulence is suppressed as polymer molecules appear to interfere with the turbulent burst processes. This suppression of turbulence in turn allows the fluid to experience a reduced amount of drag which is manifested by a decrease in the fluid friction.

The turbulent flow of a drag reduced solution displays three different regions, (N), (P), and (R) as shown in Figure 1. At lower flow rates a Newtonian region, (N), is observed and is described by Equation (1). Once a critical wall shear stress is exceeded, the friction factor is reduced below that observed for Newtonian flow. Flow in this region is termed polymeric, (P), and follows the empirical expression

$$\frac{1}{\sqrt{f}} = \delta \log \frac{\left(\frac{Re\sqrt{f}}{D}\right)}{\left(\frac{Re\sqrt{f}}{D}\right)_c} + 4.0 \log \left(\frac{3.72}{\frac{4.67}{Re\sqrt{f}} + \frac{\varepsilon}{D}}\right) \qquad (2)$$

for values of $\frac{\left(\frac{Re\sqrt{f}}{D}\right)}{\left(\frac{Re\sqrt{f}}{D}\right)_c} > 1.0$. At higher flow rates the flow becomes roughness limited, (R), and the friction factor is modelled as a constant. In Figure 1, region (P), polymeric drag reducing agents act to increase the flow, as measured by $1/\sqrt{f}$ or $v/\sqrt{\tau}$, for values of the wall shear stress, as measured by $Re\sqrt{f}/D = \sqrt{\frac{2g_c\rho}{\mu^2}}\sqrt{\tau}$, greater than a critical wall shear stress.

This critical wall shear stress is independent of the polymer concentration in the solution, as well as the pipe diameter and roughness. It is shifted to smaller values by increasing the molecular weight of the polymer. $\delta$ is the Prandtl-Karman slope increment of the polymeric curve, (P), and is defined by Equation (2). $\delta$ is found to vary approximately as the polymer concentration to a fractional power, nearly 1/2, and also increases with increasing molecular weight.

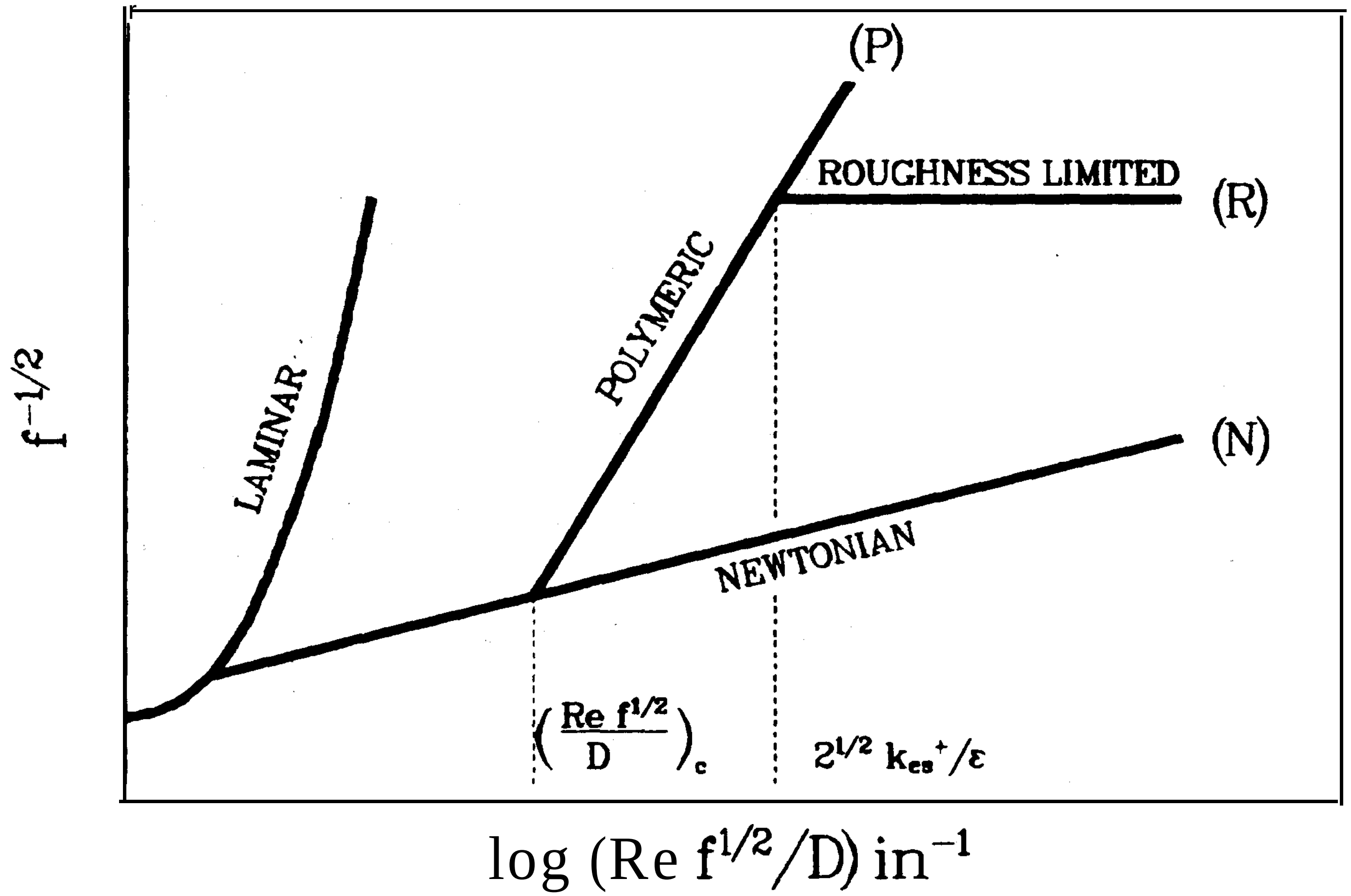


**Figure 1.** Schematic of friction factor *versus* Reynolds Number on Prandtl–Karman coordinates. Note that the ordinate is directly proportional to the velocity divided by the root of the wall shear stress and the abscissa is directly proportional to the logarithm of the wall shear stress.

Pipe roughness does not affect the critical wall shear stress or flow in the effectively smooth polymeric region, region (P). At higher wall shear stresses (region (R)), however, the flow becomes rough and the effectiveness of the polymeric agent is reduced. The upper limit of this effectively smooth region, (P), is given by

$$\left(\frac{Re\sqrt{f}}{D}\right)_{es} = \frac{\sqrt{2}\ k^{+}_{es}}{\varepsilon} \tag{3}$$

where $k^{+}_{es}$, the maximum dimensionless pipe roughness for the effectively smooth regime, is approximately 50 for a variety of conditions investigated by Virk.[11] At higher values of wall shear stress, this model describes the flow to have a constant friction factor as shown in Figure 1. The three parameters, $\left(\frac{Re\sqrt{f}}{D}\right)_c$, $\left(\frac{Re\sqrt{f}}{D}\right)_{es}$, and $\delta$ completely define the polymeric aspects of a DRA solution. The determination of the values of these parameters is the main focus of the next two sections.

## C. SCALING PARAMETERS

The relationship between Reynolds number and friction factor in reduced drag solutions is deterministic in nature. By this we mean that the relationship between Reynolds number and friction factor is determined by the value of several parameters. Hence, the scaling of small-scale test data to that which may be expected in a full size pipeline involves two steps. The first of these is model verification for the polymer solutions and the environments considered. The second step involves the determination of parameters which may then be used to predict flow in any other situation.

These parameters are:

(1) the critical wall shear stress, $\tau = \left(\frac{Re\sqrt{f}}{D}\right)_c^2 \frac{\mu^2}{2g_c\rho}$

(2) the Prandtl-Karman slope increment as a function of polymer concentration, $\delta = b(c)$,

(3) pipe roughness in both scaled test and the full size pipeline, $\varepsilon$, and,

(4) the maximum dimensionless pipe roughness for the effectively smooth regime, $k^{+}_{es}$.

Using these parameters, the concentration-dependent performance of drag reducing agents for full-scale application may be estimated.

## D. ANALYSIS OF SOUTHWEST RESEARCH INSTITUTE DATA [3]

An analysis of 30 drag reducing polymers from 11 different manufacturers was performed at Southwest Research Institute under Sandia Rational Laboratories Contract #47-2033, and the results were presented in "Brine/Polymer Mixture Drag Reduction Characteristics" by Edgar B. Bowles, Jr. [3] This evaluation was performed in a flow loop consisting of a reservoir tank, weigh tank, pump, and a series arrangement of a C-inch diameter pipe, 4-inch-diameter pipe, and a 2-inch-diameter pipe as shown in Figure 2. Polymer solution was taken out of the reservoir tank, through the pump and flow loop and then back to the reservoir tank. When it was time to collect data, the flow would then be diverted to the weigh tank to provide a flow rate measurement. Instrumentation also provided pressure drop data continuously. Reynolds numbers and friction factors were derived from the data and are presented in Table 1. Since the fluid flowed through each of the three legs in series, three different wall shear stress conditions were obtained simultaneously for each polymer solution. These data allowed for a rapid screening of many candidate DRA. Data were typically gathered at one concentration which reflected the price of the polymer and the cost structure of the pumping operations. Synthetic sodium chloride brine was used in these tests.

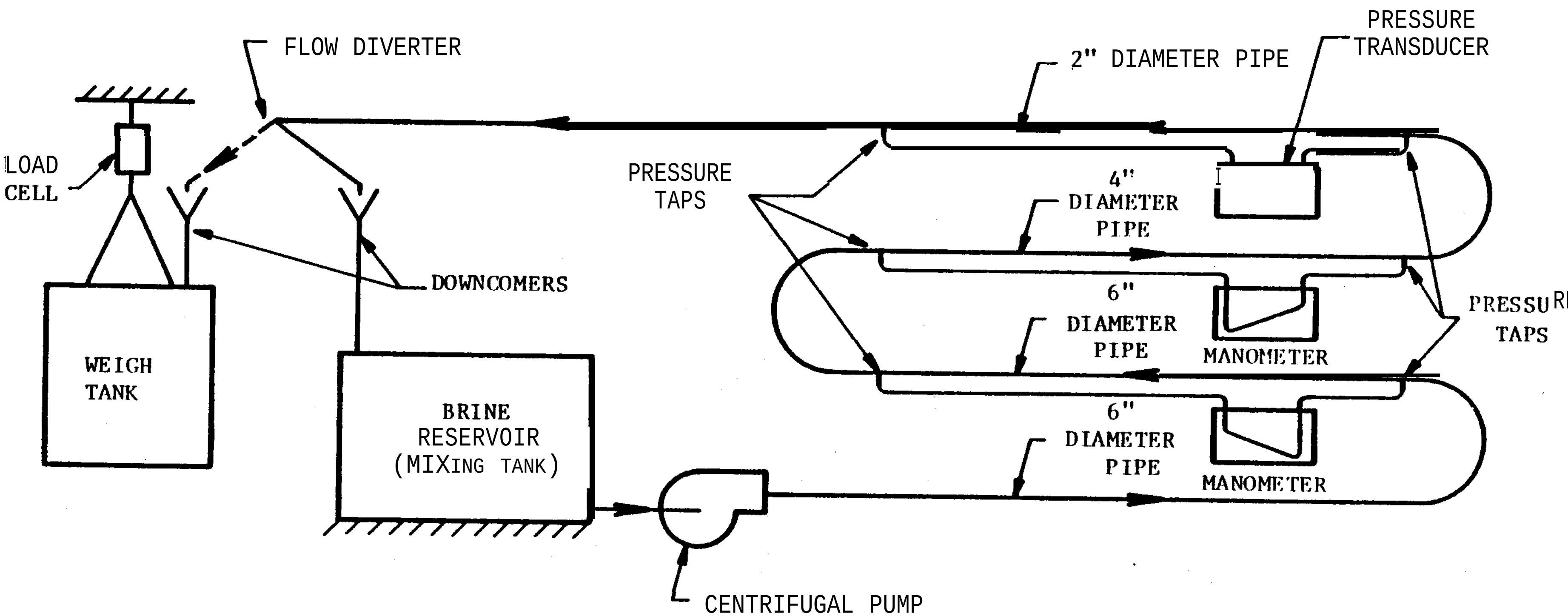


FIGURE 2. FLOW LOOP SCHEMATIC FOR

SOUTHWEST RESEARCH INSTITUTE EVALUATION (3)

TABLE 1. SUMMARY OF TEST RESULTS FOR POLYMER ADDITIVE BRINE FLOW TESTS AT SwRI

| | | | | | 40 FT LONG 6" DIAMETER PIPE | | | | 40 FT LONG 4" DIAMETER PIPE | | | | 20 FT LONG 2" DIAMETER PIPE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| POLY NO. | CONC. (PPM) | TEST TIME (MIN) | FLOW RATE (GPM) | INCR. FLOW RATE (%) | PRES. DROP (PSIG) | FLOW VEL. (FT/S) | RE. NUMBER | FRIC. FACT. | PRES. DROP (PSIG) | FLOW VBL. (FT/S) | RE. NUMBER | FRIC. FACT | PRES. DROP (PSIG) | FLOW VEL. (FT/S) | RE. NUMBER | FRIC. FACT. |
| | 0 | 3 | 326.0 | 0.0 | 0.22 | 3.70 | 107096 | 0.025 | 1.42 | 8.32 | 160547 | 0.021 | 17.0 | 33.29 | 321190 | 0.016 |
| 23 | 110 | 3 | 486.8 | 49.3 | 0.31 | 5.52 | 159775 | 0.016 | 1.42 | 12.43 | 239856 | 0.010 | 12.0 | 49.71 | 479615 | 0.005 |
| | | 28 | 404.8 | 24.2 | 0.34 | 4.59 | 132856 | 0.026 | 1.86 | 10.34 | 199526 | 0.018 | 13.9 | 41.34 | 398859 | 0.008 |
| 21 | 110 | 5 | 460.9 | 41.4 | 0.32 | 5.23 | 151381 | 0.018 | 1.42 | 11.77 | 227120 | 0.011 | 11.6 | 47.07 | 454143 | 0.006 |
| | | 28 | 422.7 | 29.7 | 0.37 | 4.80 | 138935 | 0.025 | 1.87 | 10.79 | 208209 | 0.017 | 14.0 | 43.17 | 416515 | 0.008 |
| 21 | 55 | 5 | 413.6 | 26.9 | 0.31 | 4.69 | 135751 | 0.022 | 1.54 | 10.56 | 203771 | 0.014 | 12.9 | 42.24 | 407542 | 0.008 |
| | | 29 | 375.1 | 15.1 | 0.31 | 4.26 | 123305 | 0.027 | 1.82 | 9.58 | 184860 | 0.021 | 14.5 | 38.31 | 369624 | 0.010 |
| 23 | 55 | 3 | 407.0 | 24.9 | 0.30 | 4.62 | 133725 | 0.022 | 1.57 | 10.39 | 200491 | 0.015 | 14.1 | 41.56 | 400981 | 0.009 |
| | | 28 | 380.5 | 16.7 | 0.30 | 4.32 | 125041 | 0.025 | 1.85 | 9.71 | 187369 | 0.020 | 15.1 | 38.86 | 374931 | 0.010 |
| 1 | 36 | 3 | 407.0 | 24.9 | 0.30 | 4.62 | 133725 | 0.022 | 1.48 | 10.39 | 200491 | 0.014 | 13.7 | 41.56 | 400981 | 0.008 |
| | | 28 | 380.2 | 16.6 | 0.28 | 4.31 | 124752 | 0.024 | 1.72 | 9.71 | 187369 | 0.019 | 14.9 | 38.83 | 374642 | 0.010 |
| 22 | 110 | 5 | 400.5 | 22.9 | 0.32 | 4.54 | 131409 | 0.024 | 1.54 | 10.23 | 197403 | 0.015 | 13.3 | 40.90 | 394613 | 0.008 |
| | | 35 | 337.4 | 22.9 | 0.28 | 3.83 | 110858 | 0.030 | 1.76 | 8.61 | 166143 | 0.025 | 15.2 | 34.46 | 332479 | 0.013 |
| 23 | 25 | 3 | 387.2 | 18.8 | 0.30 | 4.39 | 127067 | 0.024 | 1.61 | 9.89 | 190842 | 0.017 | 14.7 | 39.54 | 381492 | 0.010 |
| | | 28 | 346.6 | 6.3 | 0.24 | 3.93 | 113753 | 0.024 | 1.65 | 8.85 | 170774 | 0.022 | 15.8 | 35.40 | 341548 | 0.013 |
| 10 | 60 | 3 | 379.5 | 16.4 | 0.30 | 4.31 | 124752 | 0.025 | 1.61 | 9.69 | 186983 | 0.018 | 15.0 | 38.76 | 373966 | 0.010 |
| 18 | 60 | 5 | 377.8 | 15.9 | 0.28 | 4.29 | 124173 | 0.024 | 1.44 | 9.65 | 186211 | 0.016 | 14.6 | 38.58 | 372230 | 0.010 |
| | | 28 | 369.9 | 13.5 | 0.27 | 4.20 | 121568 | 0.024 | 1.48 | 9.44 | 182159 | 0.017 | 14.8 | 37.78 | 364511 | 0.011 |
| 19 | 60 | 2 | 367.8 | 12.8 | 0.23 | 4.17 | 120700 | 0.020 | 1.48 | 9.39 | 181194 | 0.018 | 14.8 | 37.56 | 362388 | 0.011 |
| | | 30 | 368.1 | 12.9 | 0.28 | 4.18 | 120989 | 0.025 | 1.50 | 9.40 | 181387 | 0.018 | 15.2 | 37.59 | 362678 | 0.011 |
| 9 | 60 | 3 | 361.9 | 11.0 | 0.26 | 4.11 | 118963 | 0.024 | 1.54 | 9.24 | 178300 | 0.019 | 15.4 | 36.96 | 356599 | 0.012 |
| 17 | 40 | 3 | 361.2 | 10.8 | 0.26 | 4.10 | 118673 | 0.024 | 1.42 | 9.22 | 177914 | 0.017 | 15.2 | 36.89 | 355924 | 0.012 |
| 10 | 30 | 3 | 355.5 | 9.1 | 0.24 | 4.03 | 116647 | 0.023 | 1.43 | 9.08 | 175212 | 0.018 | 15.2 | 36.31 | 350328 | 0.012 |
| | | 28 | 336.3 | 3.2 | 0.26 | 3.82 | 110569 | 0.028 | 1.57 | 8.59 | 165757 | 0.022 | 15.6 | 34.34 | 331321 | 0.014 |
| 8 | 60 | 3 | 347.7 | 6.7 | 0.32 | 3.95 | 114332 | 0.032 | 1.60 | 8.88 | 171353 | 0.021 | 15.6 | 35.51 | 342609 | 0.013 |
| 26 | 60 | 3 | 328.6 | 0.8 | 0.23 | 3.73 | 107964 | 0.025 | 1.42 | 8.39 | 161898 | 0.021 | 17.3 | 33.56 | 323795 | 0.016 |
| 27 | 60 | 3 | 328.0 | 0.6 | 0.23 | 3.72 | 107674 | 0.026 | 1.44 | 8.37 | 161512 | 0.021 | 17.3 | 33.50 | 323216 | 0.016 |

TABLE 1. SUMMARY OF TEST RESULTS FOR POLYMER ADDITIVE BRINE FLOW TESTS AT SwRI (CONTINUED)

| POLY NO | CONC. (PPM) | TEST TIME (MIN) | FLOW RATE (GPM) | INCR. FLOW RATE (%) | 40 FT LONG 6" DIAMETER PIPE PRES. DROP (PSIG) | FLOW VEL. (FT/S) | RE. NUMBER | FRIC. FACT. | 40 FT LONG 4" DIAMETER PIPE PRES. DROP (PSIG) | FLOW VEL. (FT/S) | BE. NUMBER | FRIC. FACT | 20 FT LONG 2" DIAMETER PIPE PRES. DROP (PSIG) | FLOW VEL. (FT/S) | RE. NUMBER | FRIC. FACT. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 60 | 3 | 328.0 | 0.6 | 0.22 | 3.72 | 107674 | 0.024 | 1.43 | 8.37 | 161512 | 0.021 | 17.3 | 33.50 | 323216 | 0.016 |
| 12 | 36 | 3 | 326.9 | 0.3 | 0.23 | 3.71 | 107385 | 0.026 | 1.42 | 8.35 | 161126 | 0.021 | 17.0 | 33.40 | 322252 | 0.016 |
| 14 | 60 | 3 | 322.6 | -1.0 | 0.23 | 3.66 | 105938 | 0.026 | 1.39 | 8.24 | 159003 | 0.021 | 16.7 | 32.95 | 317910 | 0.016 |
| 24 | 110 | 3 | 322.2 | -1.2 | 0.22 | 3.66 | 105938 | 0.025 | 1.66 | 8.23 | 158810 | 0.026 | 17.5 | 32.90 | 317427 | 0.017 |
| | 0 | 3 | 327.7 | 0.0 | 0.22 | 3.72 | 107674 | 0.026 | 1.43 | 8.37 | 161512 | 0.021 | 17.1 | 33.47 | 322927 | 0.016 |
| | 0 | 3 | 325.7 | 0.0 | 0.22 | 3.70 | 107096 | 0.026 | 1.44 | 8.32 | 160547 | 0.022 | 17.4 | 33.26 | 320901 | 0.016 |
| | 0 | 3 | 325.5 | 0.0 | 0.22 | 3.69 | 106806 | 0.026 | 1.44 | 8.31 | 160354 | 0.022 | 17.0 | 33.24 | 320708 | 0.016 |
| | 0 | 3 | 330.0 | 0.0 | 0.24 | 3.74 | 108253 | 0.026 | 1.43 | 8.43 | 162610 | 0.021 | 17.2 | 33.70 | 325146 | 0.016 |
| | 0 | 3 | 330.1 | 0.0 | 0.22 | 3.75 | 108543 | 0.025 | 1.39 | 8.43 | 162610 | 0.021 | 16.8 | 33.71 | 325243 | 0.016 |
| | 0 | 3 | 329.2 | 0.0 | 0.22 | 3.74 | 108253 | 0.024 | 1.44 | 8.40 | 162091 | 0.021 | 17.6 | 33.62 | 324374 | 0.016 |
| | 0 | 3 | 328.6 | 0.0 | 0.22 | 3.73 | 107981 | 0.024 | 1.43 | 8.39 | 161898 | 0.021 | 17.2 | 33.56 | 323795 | 0.016 |
| | 0 | 3 | 326.9 | 0.0 | 0.22 | 3.71 | 107385 | 0.025 | 1.43 | 8.35 | 161126 | 0.021 | 17.3 | 33.38 | 322059 | 0.016 |
| | 0 | 3 | 327.1 | 0.0 | 0.22 | 3.71 | 107385 | 0.026 | 1.44 | 8.35 | 161126 | 0.022 | 17.3 | 33.41 | 322348 | 0.016 |
| | 0 | 3 | 326.0 | 0.0 | 0.22 | 3.70 | 107096 | 0.025 | 1.43 | 8.32 | 160547 | 0.022 | 17.0 | 33.29 | 321190 | 0.016 |
| | 0 | 3 | 324.2 | 0.0 | 0.22 | 3.68 | 106517 | 0.025 | 1.44 | 8.28 | 159775 | 0.022 | 17.1 | 33.11 | 319454 | 0.016 |
| | 0 | 3 | 324.5 | 0.0 | 0.22 | 3.68 | 106517 | 0.022 | 1.42 | 8.28 | 159775 | 0.022 | 17.1 | 33.14 | 319743 | 0.016 |
| | 0 | 3 | 329.2 | 0.0 | 0.22 | 3.74 | 108253 | 0.024 | 1.44 | 8.41 | 162284 | 0.021 | 16.7 | 33.62 | 324374 | 0.015 |
| | 0 | 3 | 323.0 | 0.0 | 0.22 | 3.67 | 106227 | 0.025 | 1.43 | 8.25 | 159196 | 0.022 | 16.3 | 32.99 | 318296 | 0.016 |
| | 0 | 3 | 327.4 | 0.0 | 0.22 | 3.72 | 107674 | 0.024 | 1.48 | 8.36 | 161319 | 0.022 | 16.8 | 33.44 | 322638 | 0.016 |
| | 0 | 3 | 324.0 | 0.0 | 0.22 | 3.68 | 106517 | 0.025 | 1.46 | 8.27 | 159582 | 0.022 | 16.6 | 33.09 | 319261 | 0.016 |

## E. DATA REDUCTION

The data for flow with no drag reducing agents, DRA, added to the brine solution may be used to determine the pipe roughness in each leg of the flow loop. Pipe roughness for brine flowing in pipe may be determined by applying Equation (1). When this is done, the pipe roughnesses given in Table 2 are obtained.

**TABLE 2**

PIPE ROUGHNESS FOR SwRI FLOW TESTS

| PIPE DIAMETER | RELATIVE ROUGHNESS ($\epsilon/D$) | LIMIT OF SMOOTH REGION $\left(\frac{Re\sqrt{f}}{D}\right)_{es}$ (l/inches) |
|---|---|---|
| 2 | 0.00017 | 208000 |
| 4 | 0.00100 | 17700 |
| 6 | 0.00195 | 6040 |

These pipe roughnesses may then be used to determine the upper limit of the effectively smooth regime as in Equation (3). These values are also shown in Table 2. As long as $Re\sqrt{f}/D$ is less than this upper limit, the wall roughness will not diminish the drag reduction effect of the polymers, and Equation (2) alone will describe the polymeric solution flow. In no case does the actual value of $Re\sqrt{f}/D$ exceed the effectively smooth limit in the SwRI data. Hence, the pipe roughnesses of the laboratory test loop do not reduce the polymer effectiveness. The same is not expected to be true of pipe roughnesses in the 36-inch brine pipeline.

In order to verify the model equations with the data given in Table 1, we plot

$$\frac{1}{\sqrt{f}} - 4.0 \log\left(\frac{3.72}{\frac{4.67}{Re\sqrt{f}} + \frac{\varepsilon}{D}}\right) = \frac{1}{\sqrt{f_p}} - \frac{1}{\sqrt{f_s}} \qquad (4)$$

against the abscissa

$$\log \frac{Re\sqrt{f}}{D}$$

where the subscript, **s**, refers to the drag expected in the solvent alone evaluated at the value of $Re\sqrt{f}$ for the solution. When the data are plotted in this manner, a linear coorelation is expected in the polymeric region as presented in Equation (2). The value of the intercept on the abscissa is the critical $(Re\sqrt{f}/D)_c$ corresponding to the inception of polymeric drag reduction. The slope of the line is $\delta$. The plots for the data given in Table 1 are presented in Figures 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13.

As may be seen in Figures 3 through 13, the data do show the required linearity. Hence, values of critical wall shear stress and the slopes of the enhanced polymeric lines are shown in Table 3 for those materials which were effective.

For those cases where a polymer was tested at multiple concentrations (materials numbered 21, 23, and 10), the test data do not show a single critical wall shear stress as predicted by Virk.[10] Rather this number appears to be a function of the polymer concentration. The slope, 6, increases with concentration in a way that is not inconsistent with

$$6 = \text{constant } c^n \qquad (5)$$

where n is a constant. While data presented in Figures 3 through 13 do show that the flow model presented here is appropriate for a scale-up analysis, there is enough variance in the concentration dependence of these data to necessitate further comparisons.

=

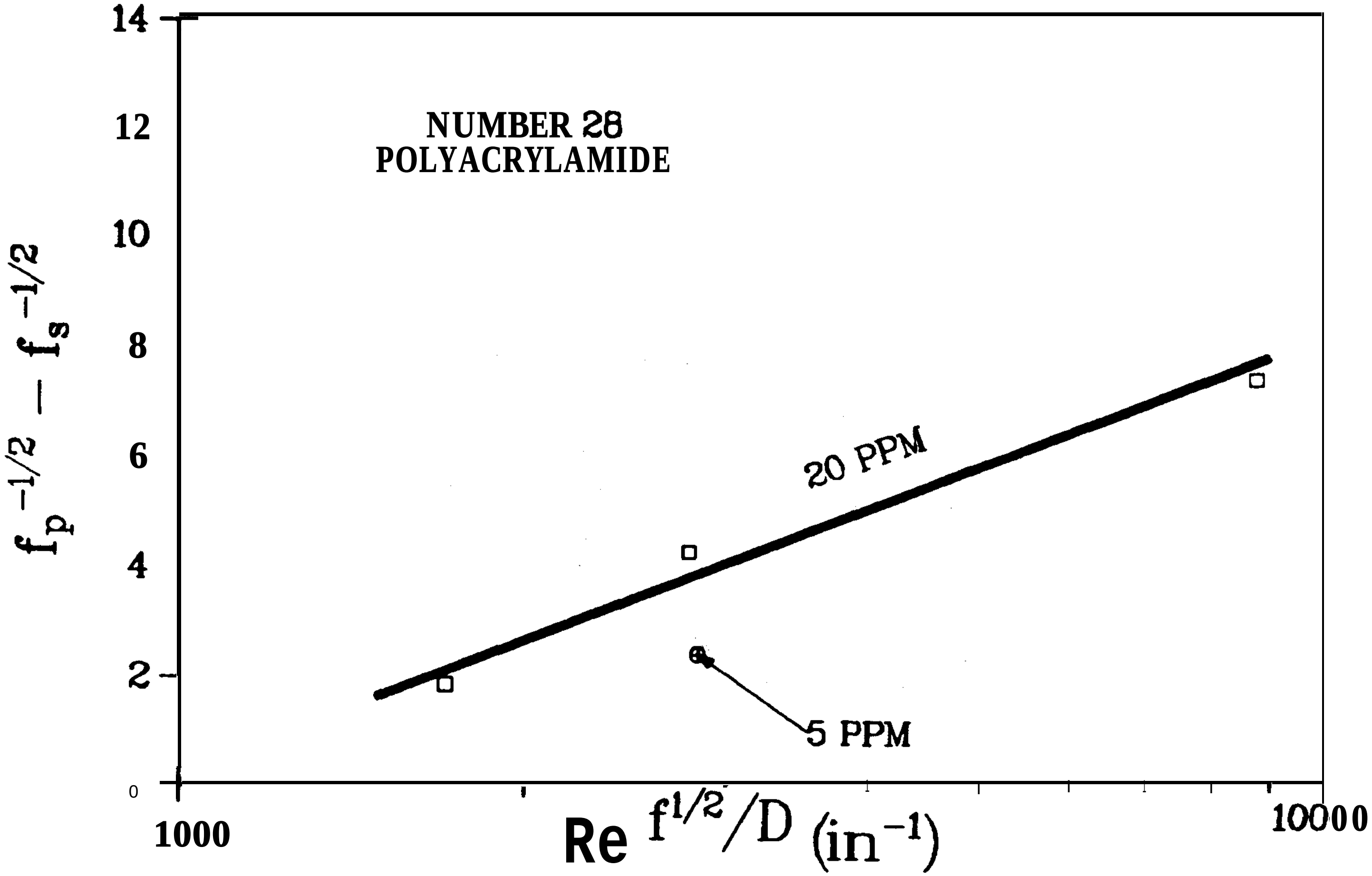


Figure 3. Plot of fractional slip versus wall shear stress for material #28. 5 ppm. data from supplier included for reference.

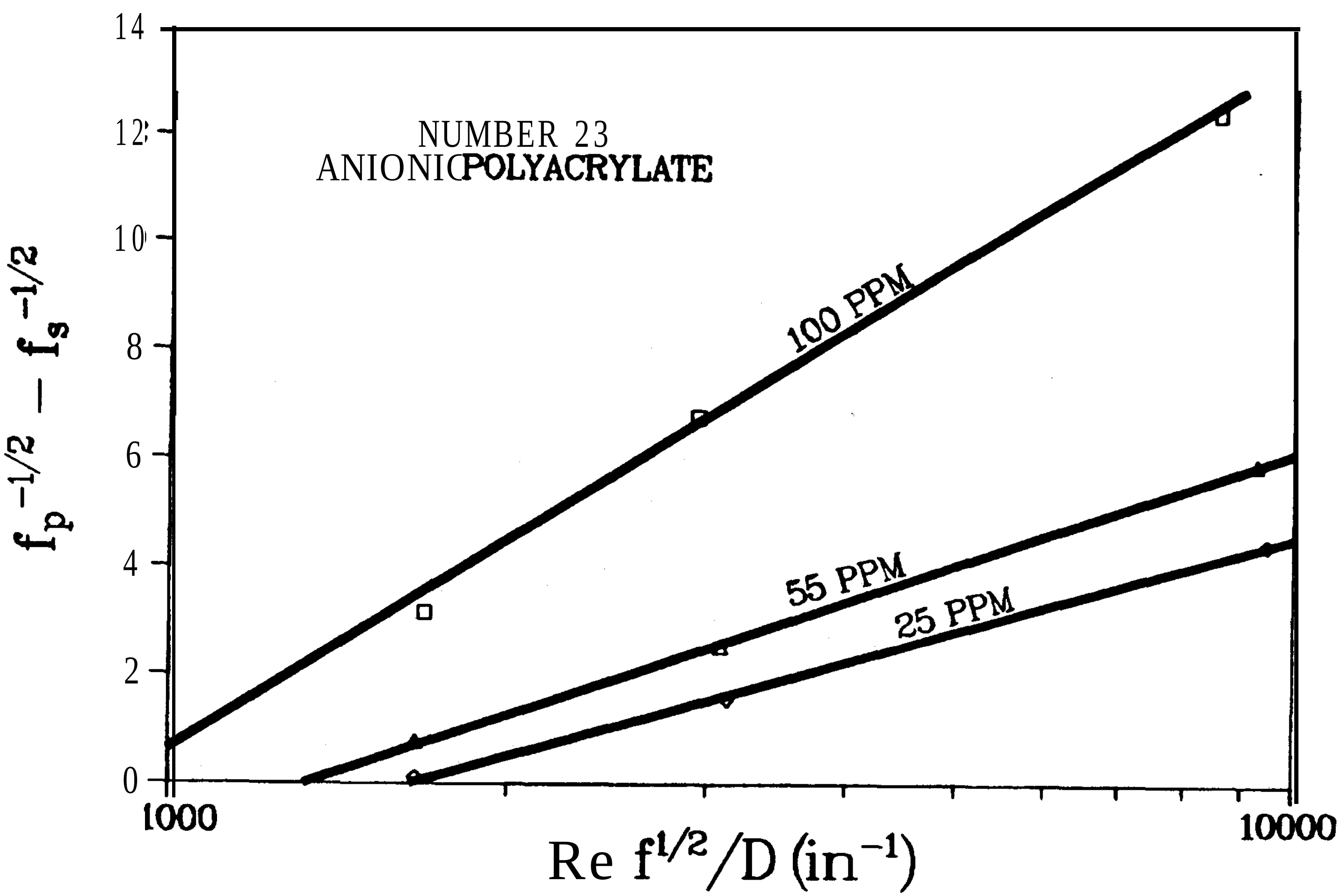


**Figure 4. Plot of fractional slip versus wall shear stress for material # 23.**

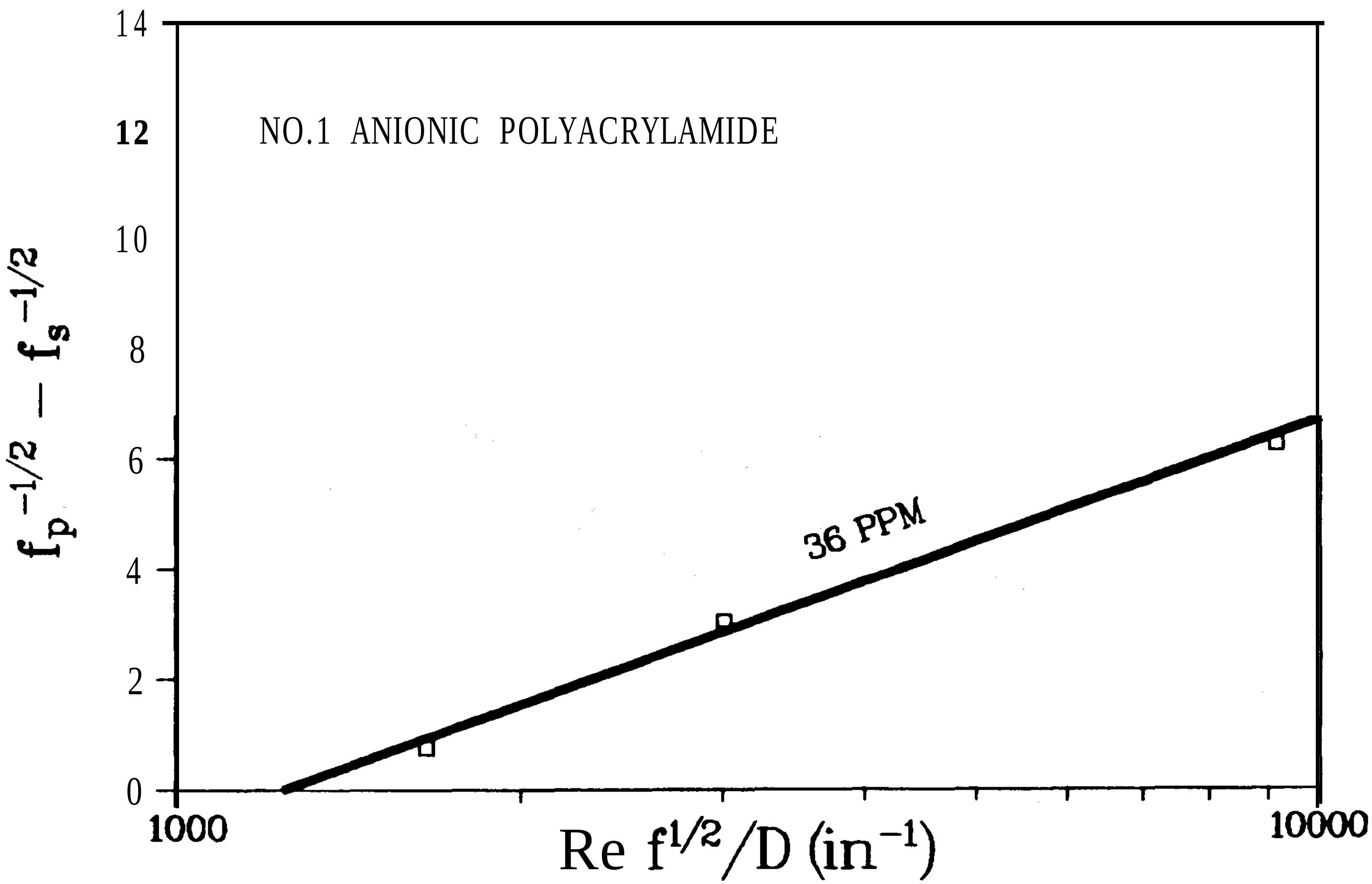


**Figure 5. Plot of fractional slip versus wall shear stress for material #1.**

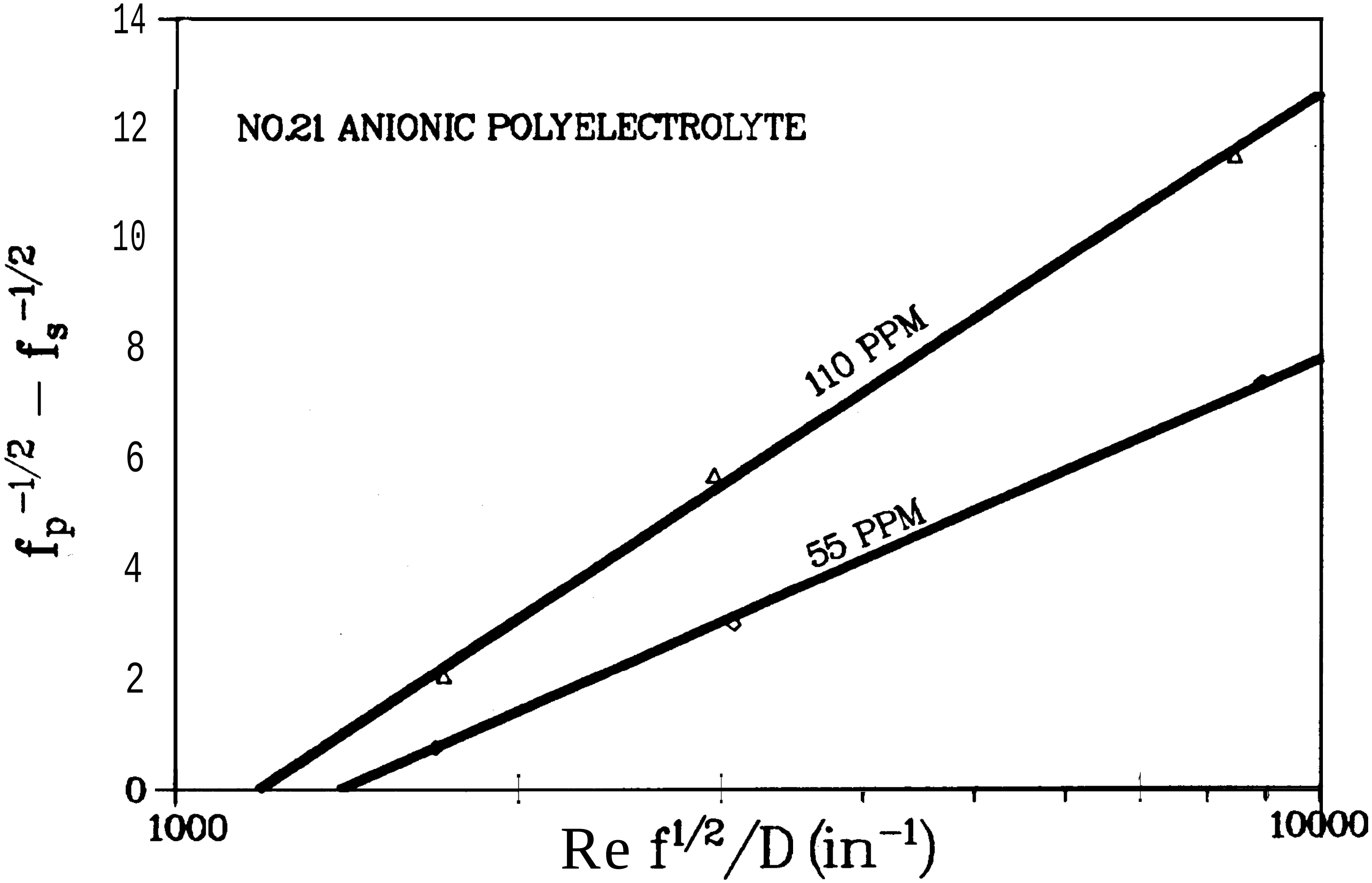


Figure 6. Plot of fractional slip versus wall shear stress for material #21.

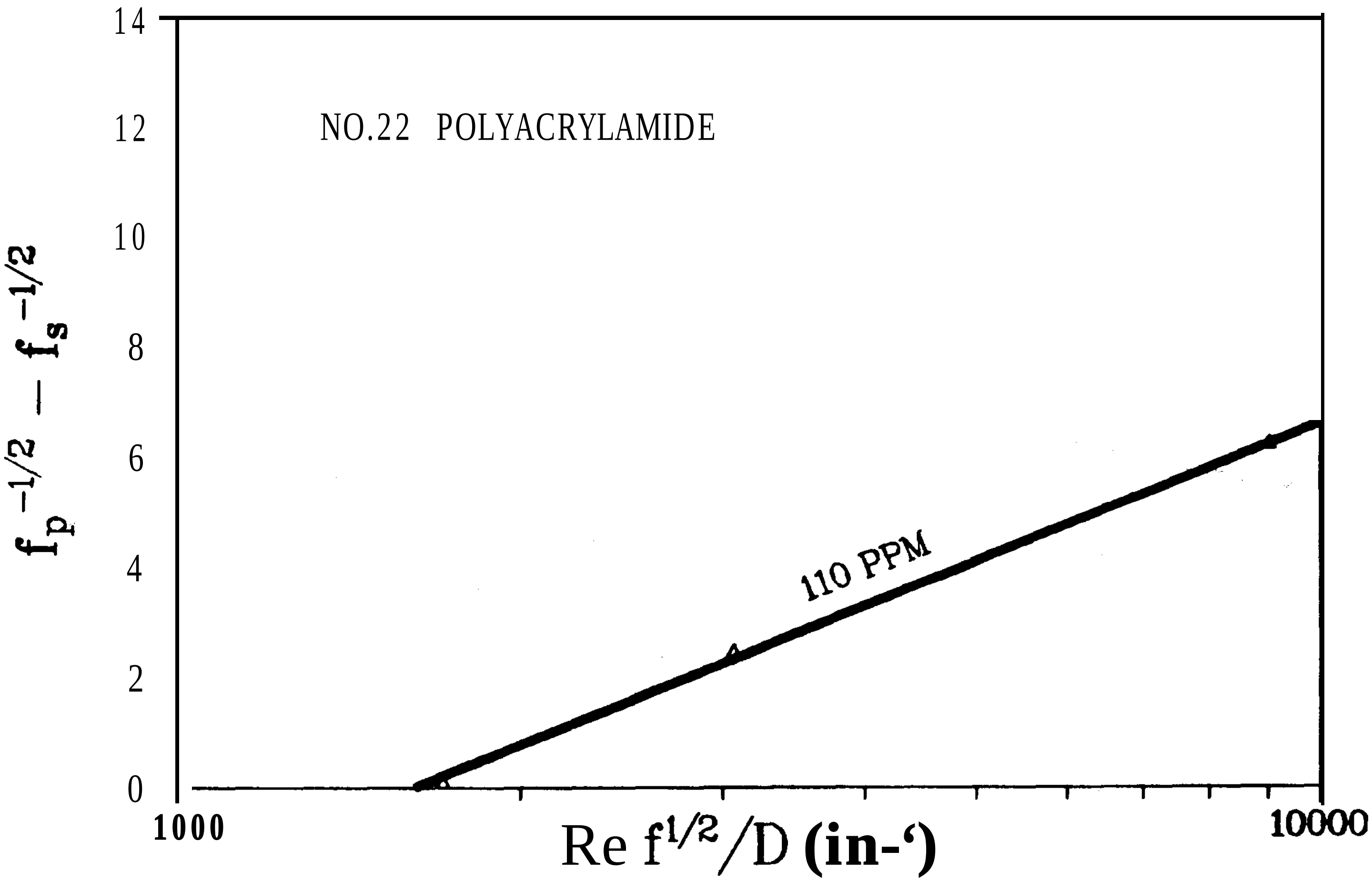


**Figure 7. Plot of fractional slip versus wall shear stress for material #22.**

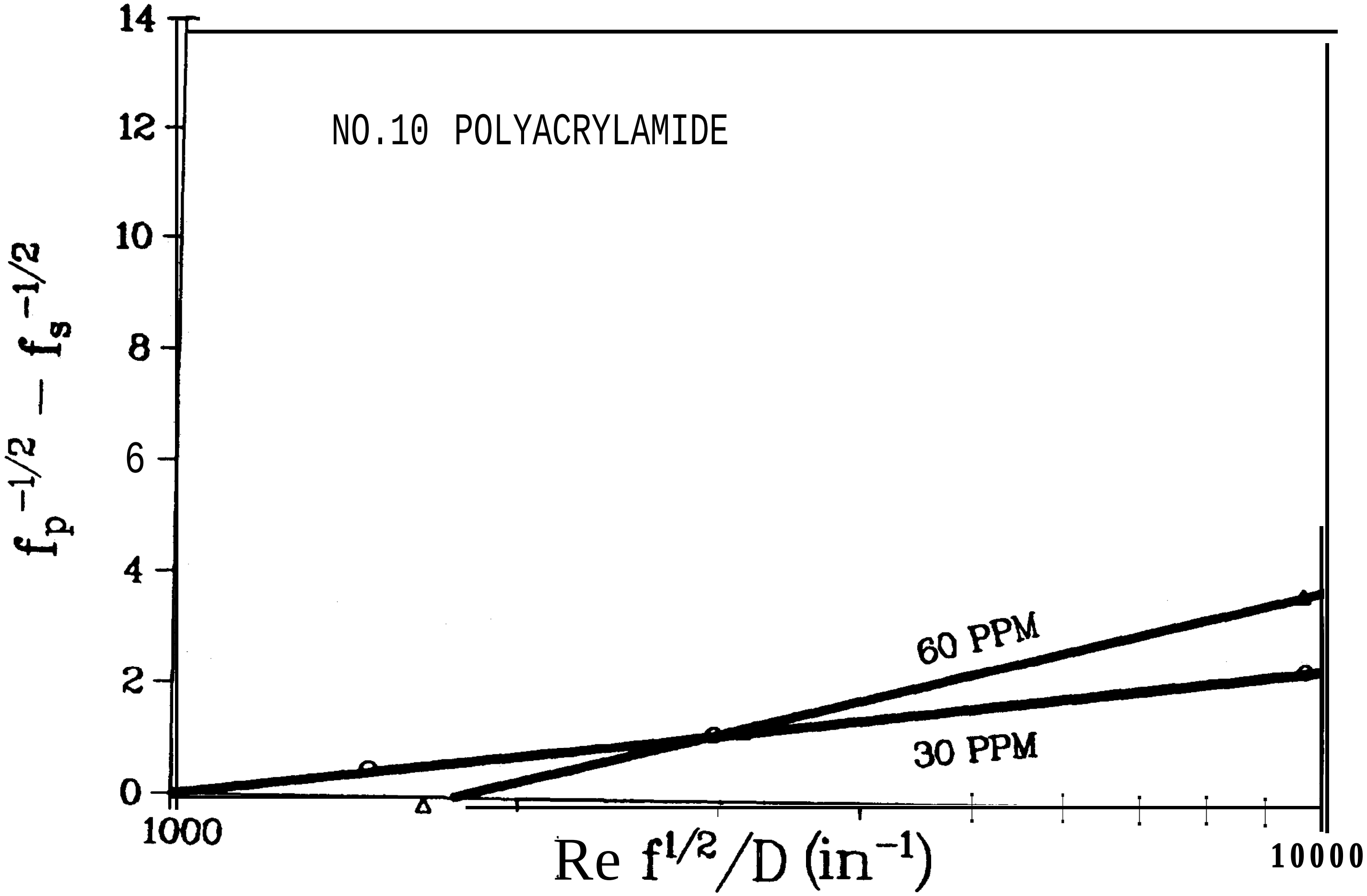


**Figure 8. Plot of fractional slip versus wall shear stress for material #10.**

3

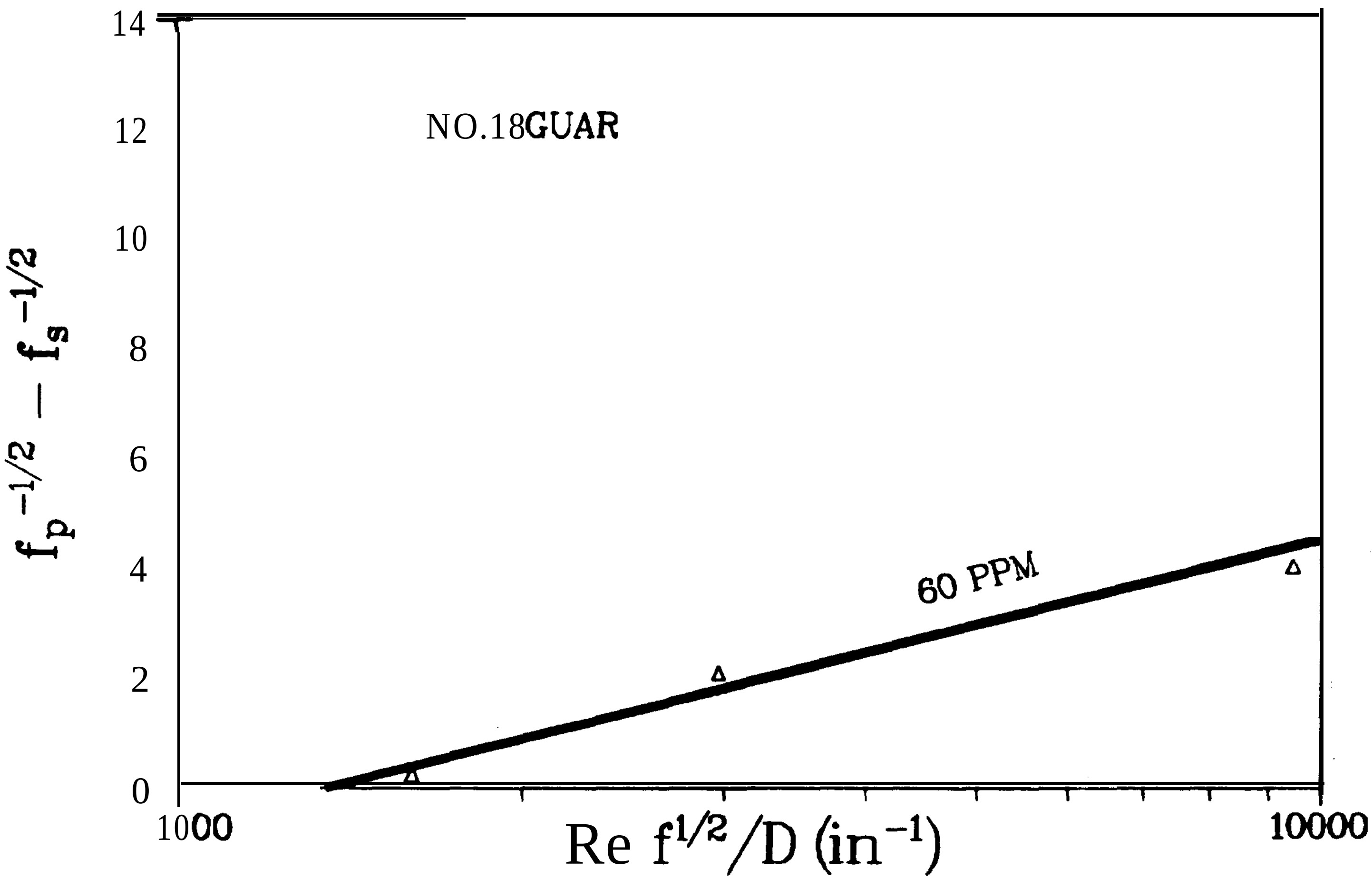


**Figure 9. Plot of fractional slip versus wall shear stress for material #18.**

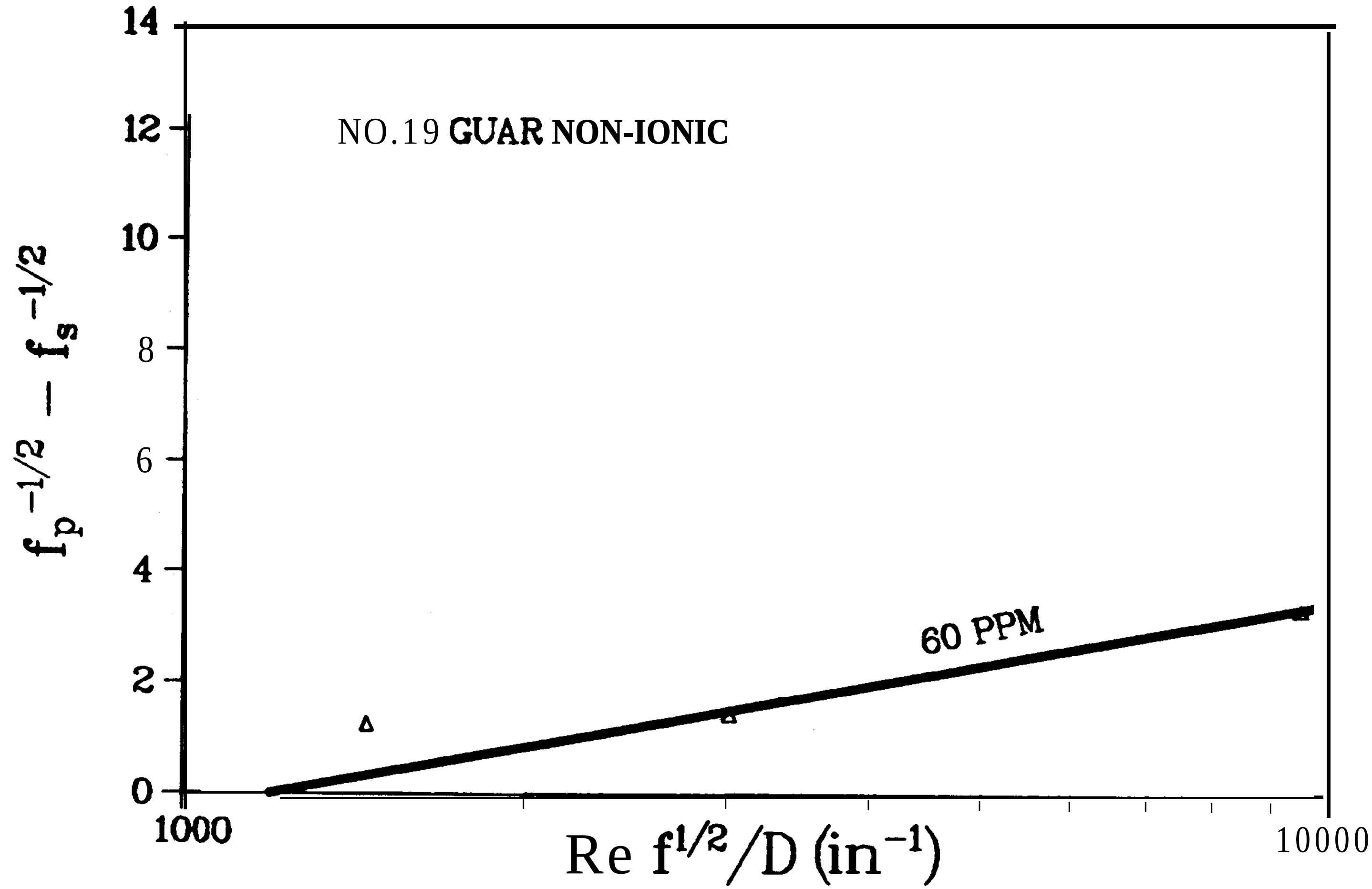


**Figure 10. Plot of fractional slip versus wall shear stress for material #19.**

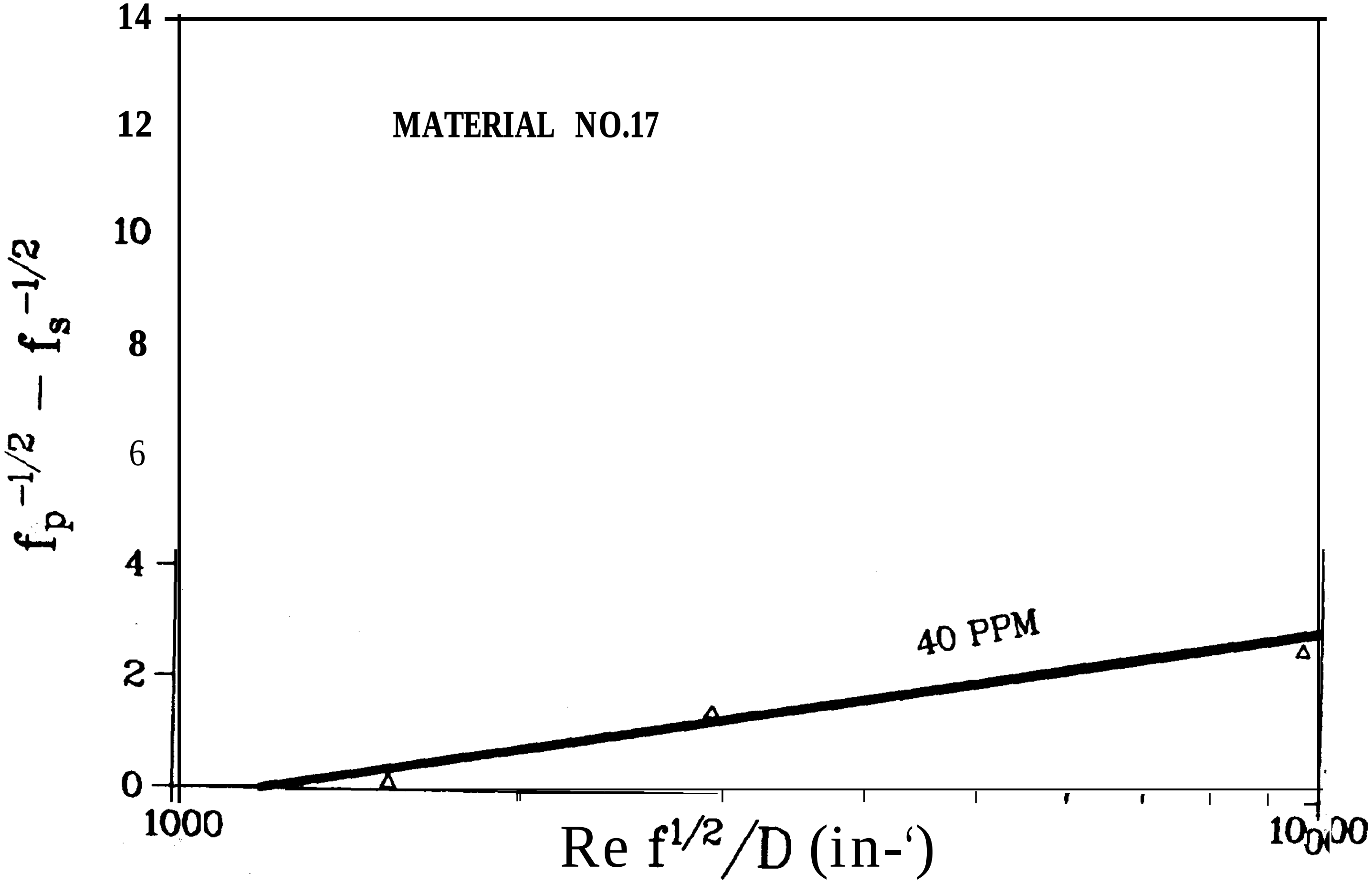


**Figure 11.** Plot **of fractional slip versus wall shear stress for material #17.**

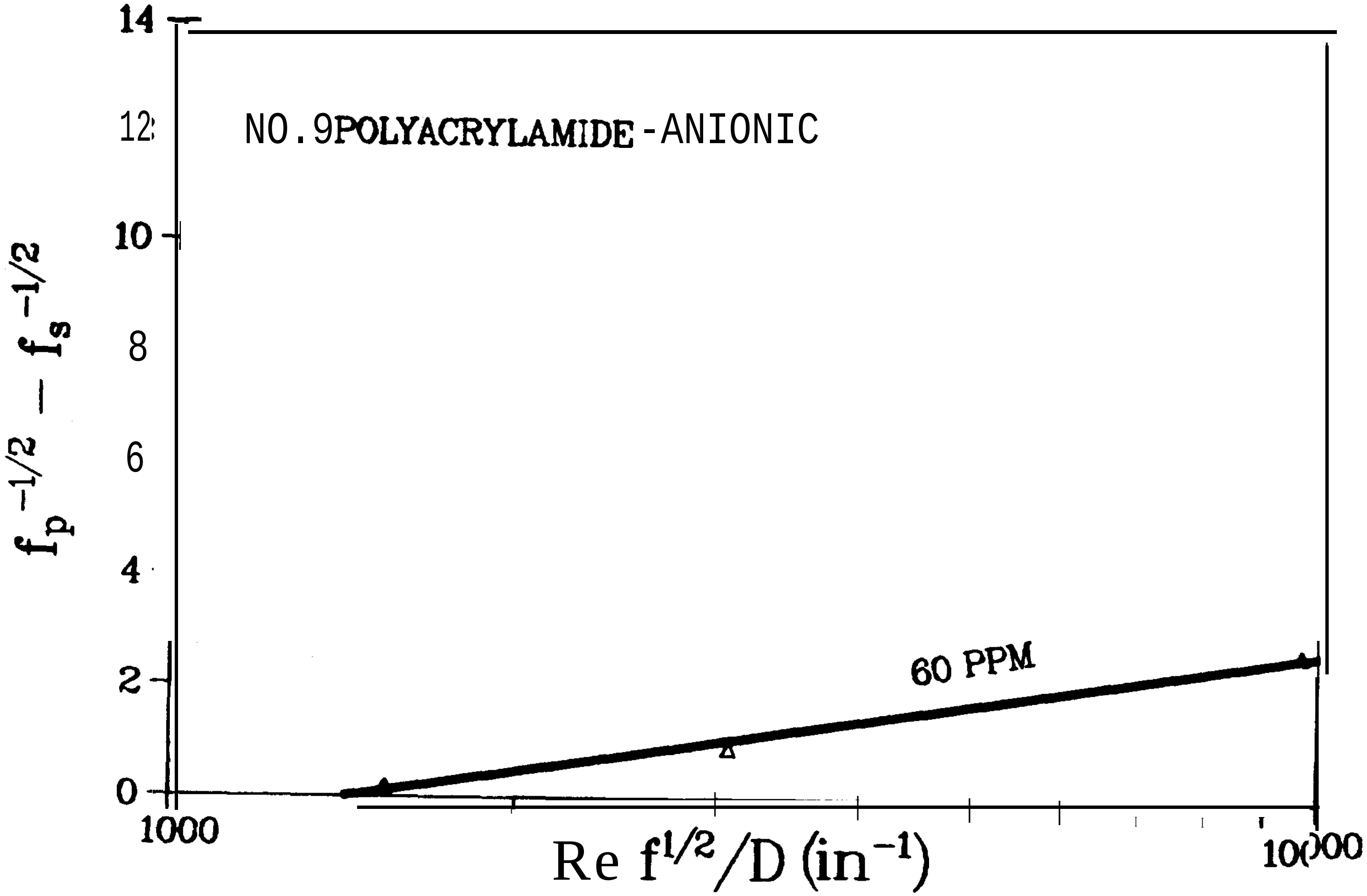


**Figure 12. Plot of fractional slip versus wall shear stress for material #9.**

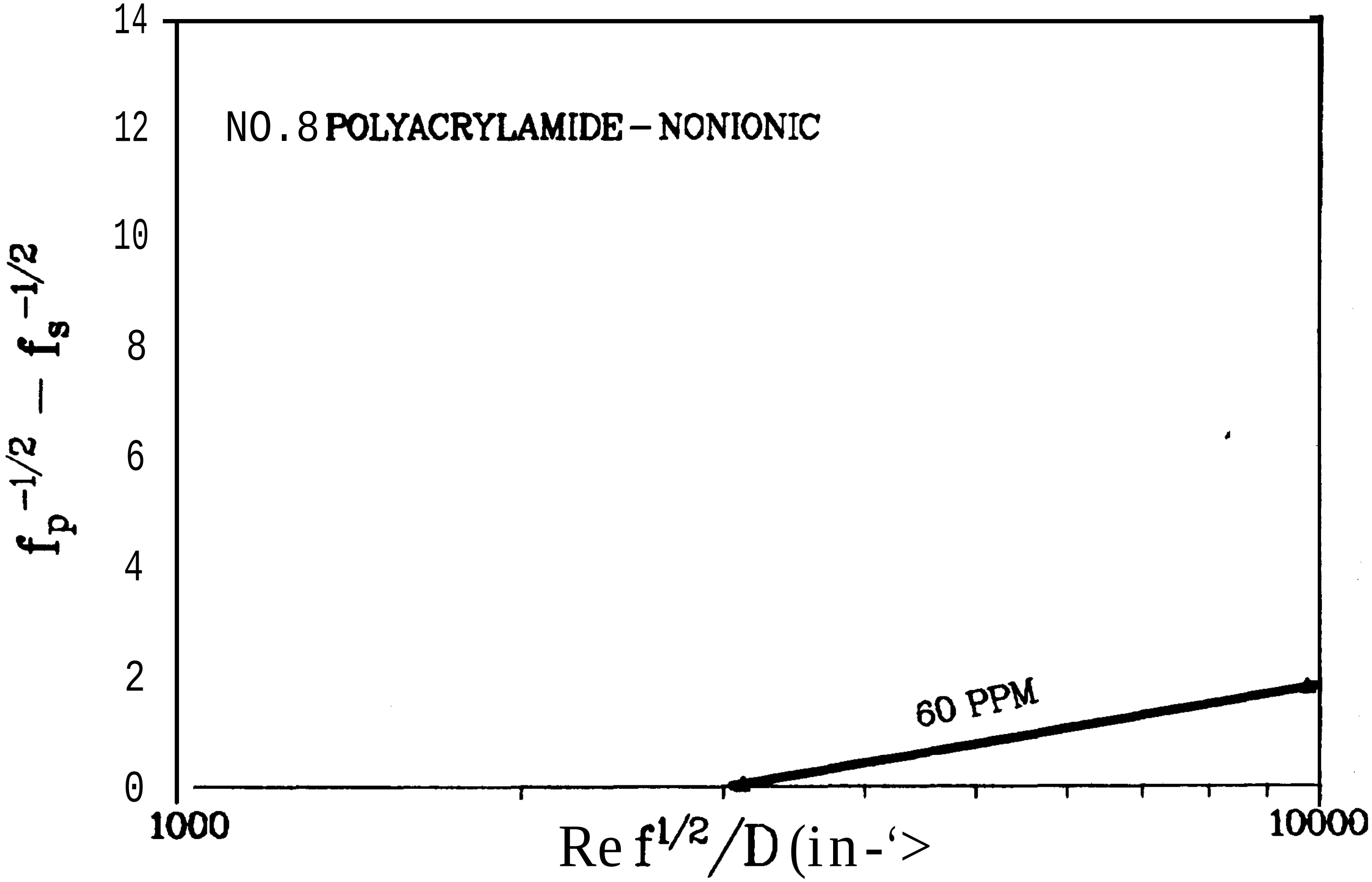


**Figure 13. Plot of fractional slip versus wall shear stress for material #8.**

TABLE 3

POLYMER SOLUTION PROPERTIES OBTAINED FROM SwRI FLOW TESTS

| MATERIAL NO. | CONCENTRATION (ppm) | $(Re\sqrt{f}/D)_c$ (1/inches) | $\delta$ |
|---|---|---|---|
| 1 | 36 | 1240 | 7.4 |
| 21 | 110 | 1180 | 13.5 |
| 21 | 55 | 1390 | 10.7 |
| 23 | 100 | 890 | 12.8 |
| 23 | 55 | 1320 | 7.0 |
| 23 | 25 | 1630 | 5.8 |
| 22 | 110 | 1620 | 8.4 |
| 18 | 60 | 1350 | 5.2 |
| 19 | 60 | 1190 | 3.7 |
| 10 | 60 | 1770 | 5.2 |
| 10 | 30 | 1000 | 2.5 |
| 9 | 60 | 1410 | 3.1 |
| 8 | 60 | 3000 | 3.5 |
| 17 | 40 | 1190 | 3.3 |
| 28 | 20 | 960 | 8.1 |

## F. WEST HACKBERRY PIPELINE CHARACTERISTICS

The ultimate use of these drag reducing agents is in brine disposal pipelines similar to the brine pipeline at West Hackberry, LA. This pipeline is 36-inch O.D. and 34.75-inch I.D. (5/8-inch wall thickness) with an actual length of 139359.4 feet (26.4 miles) and an additional 3240 feet in the diffuser section. Pipeline elevation in the diffuser section is 41.4 feet below the pump, and the brine discharge is 28.6 feet below mean sea level in the Gulf of Mexico. The diffuser section consists of 55 nozzles on 60-foot centers where each nozzle points vertically upward. Each nozzle consists of a lo-inch tee which is serially reduced through two Venturi reducers to a 3-inch I.D. and then connected to 56 inches of 3-inch I.D. tubing to give an overall nozzle length of 11.7 feet. The total brine flow through the pipeline varies with time. Recent typical throughput varies between 864.3 and 1028.3 MBBL/day while pump head pressures vary correspondingly between 584 and 770 psia. The brine is 95% NaCl saturated with a specific gravity of 1.19 and a dynamic viscosity of approximately 1.45 cp. Additionally a small amount (< 1%) of suspended solids will be carried with the brine and up to 2000 ppm of dissolved calcium will be preaent.

## G. NEWTONIAN FLOW RATE - PRESSURE DROP MODEL

The correlation of the flow rate and pressure drop through any pipeline is made by applying Equation (1) and an energy balance. In the case of the West Hackberry brine pipeline, these equations are used repeatedly in the diffuser section for each of the nozzles and the total flow through the diffuser section is matched to the total flow in the main pipeline. A numerical solution to these equations which describes brine flow in the West Hackberry pipeline has been developed. In the model the absolute pressure on the outlet of the pump must be specified. The numerical model then determines the total flow through the main pipeline and diffuser. The solution methods are presented in Appendix A.

In this report we apply this Newtonian flow model to determine the overall effective pipe roughness of the West Hackberry brine pipeline. This roughness is then used in the polymer flow model which is presented in Section I.

Although the term pipe roughness refers to a surface variation of a uniform nature on the inside of the pipe, we determine an effective roughness which encompasses the situation where sand and other **particulates** have settled out at the bottom of the pipeline, occasional weldment upsets which interrupt the flow, as well as corrosion-erosion of the pipe surface. For the recent pressure drop-flow rate information presented in Section F, a simple matching of these data leads to a pipe roughness of 0.0022 feet. This roughness is then used in Equation **(3)** to calculate a value of $(Re\sqrt{f}/D)_{es}$ of 2650 /inches. This roughness is then used to predict the performance of the pipeline when polymeric drag reducing agents are added to the flow.

## H. POLYMER FLOW RATE - PRESSURE DROP MODEL

A forecast of the performance of drag reducing agents in the West Hackberry brine pipeline may be obtained by using the previously developed **Newtonian** flow model with one change. Instead of using Equation **(1),** Equation (2) with the limitations imposed by Equation **(3)** will be used.

## I. APPLICATION OF THE POLYMER FLOW RATE - PRESSURE DROP MODEL

The variation in polymeric solution properties will have a significant effect on the drag reduction observed in the brine pipeline. There are several measures for this variation. It is possible to measure improvement in flow at a constant pressure drop, or reduction in pressure drop at constant flow, or some combination of the above. Since the primary reason for considering the use of drag reducing agents was to increase the brine line throughput, the polymer model was applied with head pressure held constant. The addition of polymer then allows increases in the flow rate as a function of pipeline roughness and polymeric properties. Curves are presented of the parametric variation of 6, the slope increment given in Equation (2); $(Re\sqrt{f}/D)_c$, the measure of the critical wall shear stress; and $\left(\frac{Re\sqrt{f}}{D}\right)_{es} = \frac{\sqrt{2}\ k^+_{es}}{c}$, the maximum roughness of the effectively smooth polymeric regime. These correlations are presented in Figures 14, 15, 16, and 17. The theory presented above calls for $\delta$ to vary as a power of the concentration, while the critical wall shear stress should be a function of the polymer type and

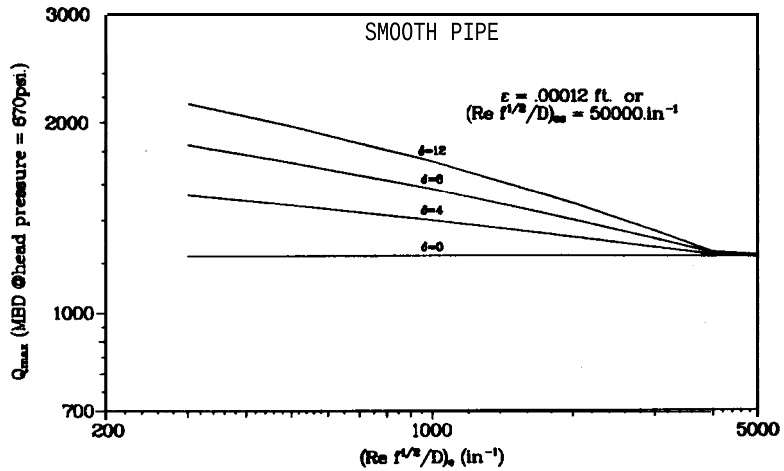


Figure 14. The variation in the maximum pumping rate in the West Hackberry pipeline as a function of polymer solution properties. $(Re\ f^{1/2}/D)_{es} = 50000(in^{-1})$ or $\varepsilon$ = .00012(ft) corresponds to smooth pipe.

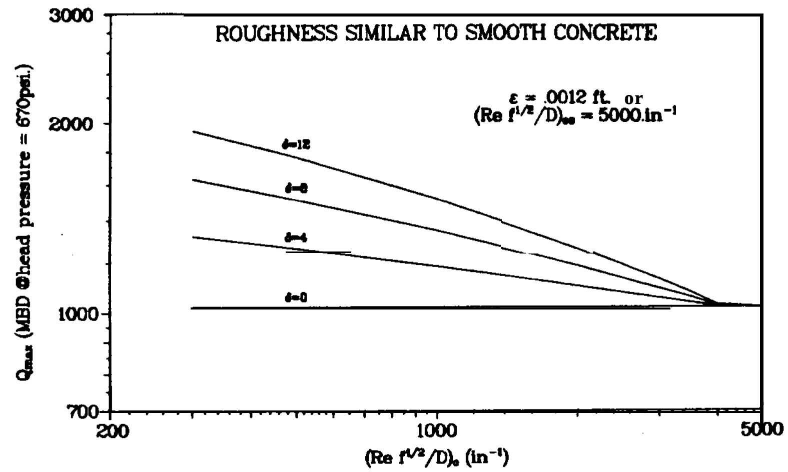


Figure 15. The variation in the maximum pumping rate in the West Hackberry pipeline as a function of polymer solution properties. $(Re\ f^{1/2}/D)_{es} = 5000(in^{-1})$ or $\varepsilon$ = .0012(ft) corresponds to smooth concrete pipe.

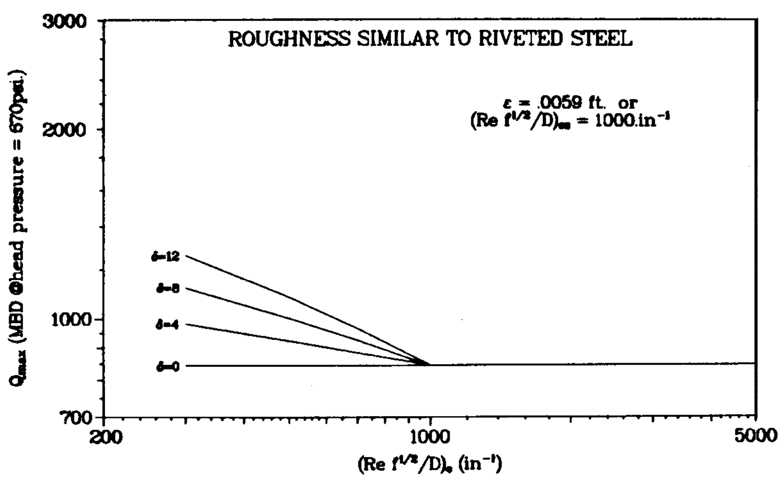


Figure 16. The variation in the maximum pumping rate in the West Hackberry pipeline as a function of polymer solution properties. $(Re\ f^{1/2}/D)_{es} = 1000(in^{-1})$ or $\varepsilon$ = .0059(ft) corresponds to riveted steel pipe.

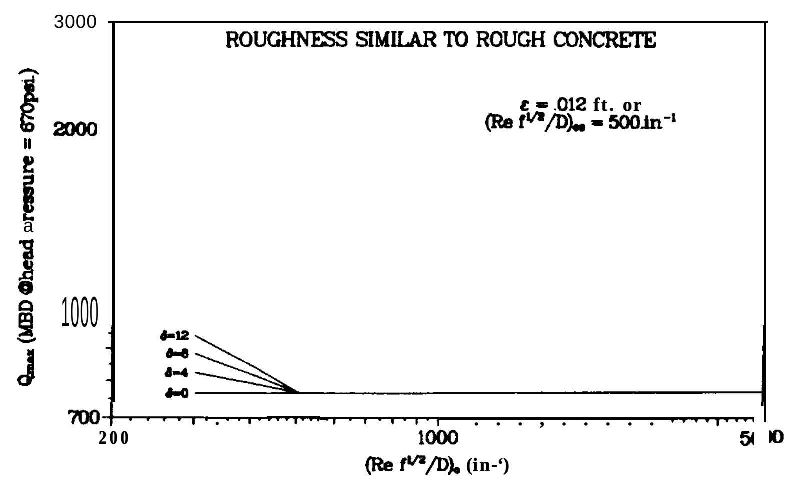


Figure 17. The variation in the maximum pumping rate in the West Hackberry pipeline as a function of polymer solution properties. $(Re\ f^{1/2}/D)_{es} = 500(in^{-1})$ or $\varepsilon$ = .012(ft) corresponds to rough concrete pipe.

molecular weight, and $(Re\sqrt{f}/D)_{es}$ should be a function of the pipe roughness. As may be seen in these figures, increasing the pipe roughness decreases the utility of the polymeric additives. Increases in polymer concentration, i.e., increasing $\delta$, increase the flow rate. Decreasing the critical wall shear stress, as through the choice of higher molecular weight polymers, also increases the flow rate. Once the polymeric material is selected, however, the control of pipeline roughness offers the best method of optimizing polymer performance. The pipeline roughness may be controlled through the periodic cleaning of the pipeline. A comparison of Figures 14 and 15 reveals that little improvement in polymer performance occurs for values of roughness less than 0.0012 feet.

## J. FIELD FLOW TEST PROCEDURE

The first phase of experimentation (the SwRI experiments) was designed to provide data to allow a quick screening of the DRA in order to reduce the number of materials to be further tested. In order to complete the analysis of the use of DRA in the brine disposal pipelines within the SPR, additional testing needs to be performed. Yet to be answered are questions about the use of field brines, shear sensitivity of the polymers, and verification of the laws of pipeline scaling. The first two of these questions will be answered by tests to be performed in a 3-inch-diameter flow loop installed as a side stream on the West Hackberry pipeline. The laws of scaling will be further investigated in a 36-inch-diameter (full--scale) test of one of the materials. The combination of these tests will allow us to complete the appraisal of the use of DRA.

A comparative analysis of the performance of the drag reducing agents shown in Table 1 will be performed in the flow loop depicted in Figure 18. This flow loop will consist of a 3-inch pipeline, together with a flow control valve to regulate the flow through the loop and pressure taps to allow measurement of the overall pressure drop. Drag reducing polymers will be mixed in an 8-gallon tank and then metered into the flow loop with a positive displacement pump, rated at 49 gallons per hour and 1050 psi, at prescribed rates to obtain the required solution concentrations. This pump should allow

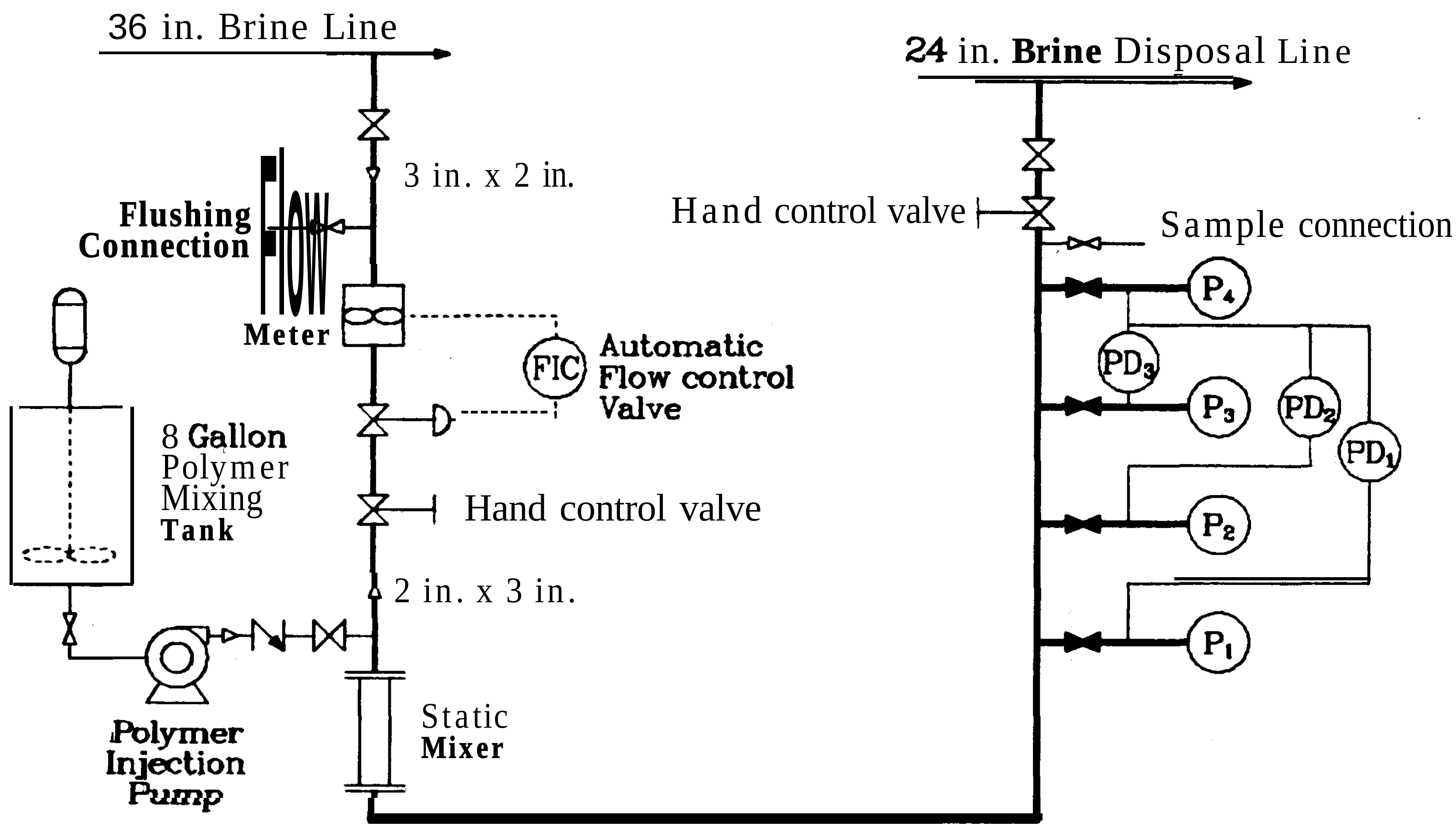


Figure 18. Schematic of polymer test loop.

polymer injection with a minimum of degradation. Similarly, the line mixer is a low shear device and there are no other constrictions in the flow path within the loop.

Flow rates to be used in this flow loop must model those which are to be used in the West Hackberry brine pipeline. It is desirable to operate this brine pipeline at a flow rate of 1.1 MMBBL/day while the pump head pressure remains near its current value of 670 psia. Under these conditions the wall shear stress in the main pipeline is 0.48 psf, and the maximum wall shear stress in the diffuser section is 6.12 psf. These wall shear stresses correspond to values of $Re\sqrt{f}/D$ of 4080/inches and 14600/inches, respectively. The limit of the effectively smooth polymeric region is at a $(Re\sqrt{f}/D)_{es}$ of 2650/inches, as was shown above. For the flow model presented above, this means that there will be flow enhancement above that expected for simple Newtonian flow for values of $Re\sqrt{f}/D$ up to 2650/inches. For larger values of $Re\sqrt{f}/D$ the friction factor will become and remain constant due to expected brine pipeline roughness. Additionally, it is expected that the flow will behave in a strictly Newtonian manner for values of $Re\sqrt{f}/D$ less than the critical value of $Re\sqrt{f}/D$ given in Table 3. Hence, for these flow tests it is important to investigate the flow region where the value of $Re\sqrt{f}/D$ varies between its critical value and the limit of the effectively smooth region (2650/inches).

The assignment of particular flow rates in the 3-inch flow loop in order to match the above given parametric values of the wall shear stress will depend on the particular polymer being tested, its critical wall shear stress, and $\delta$, the slope of the enhancement curve on Prandtl-Karman coordinates. If, for example, material #1 in Table 3 were chosen, then Equation (2) yields a volumetric flow rate of 151 gal/min corresponding to $Re\sqrt{f}/D$ of 2650/inches. In a 120-foot length of pipe this flow would experience a pressure drop of 2.68 psi. Similar calculations for the critical value of $(Re\sqrt{f}/D)_c$ of 1240 inches yield a flow rate of 57 gal/min at a pressure drop of 0.59 psi.

Since the performance of drag reducing polymers is as yet not completely defined, the parameters in Table 3 are not accurate enough to permit a complete definition of exact flow conditions. Nonetheless, we can see that it is important to define the (N) and (P) lines of Figure (1) for values of $Re\sqrt{f}/D$ up to the effectively smooth limit. In order to accomplish this, at least three data points will be taken in the SO-150 gal/min region without polymer to establish the (N) curve for the test loop. This procedure will then be repeated to establish (P) curves at three different concentration levels. The slopes of the resultant curves will then be cross-correlated to allow performance predictions at different concentration levels by way of the method implied by Equation (5). The concentrations of polymer to be tested will depend on the polymers. Since it is desired to increase the flow rate in the West Hackberry brine pipeline from roughly 850 to 1100 MBBL/day, maximum polymer concentrations will be chosen to accomplish this. Even though the polymer flow model may be applied to determine what appropriate concentration levels should be used, it is felt that the existing data would cause this amount to be overestimated. Hence, the test itself will be allowed to guide determination of the maximum concentration.

The scale up laws developed in the first phase of testing will be verified by a full-scale flow test in the 36-inch-diameter brine disposal pipeline. In this test DRA will be added at two concentrations to a pipeline operated at field pressure. The improvement in flow will be measured two ways: at constant flow rate and at the maximum pressure drop. The results of this test will allow an extrapolation of the other data to that expected in the 36-inch-diameter pipeline.

## K. PERFORMANCE PREDICTIONS

The performance of these polymers in the West Hackberry brine pipeline may be estimated by applying the results obtained from the testing in the flow model for drag reducing agents. For a sample case where $(Re\sqrt{f}/D)_c$ is 1240/inches, $\delta$ is 7.4 (as in the case of polymer #1), and $\varepsilon$ is 0.0022 feet (see Section G), the model calculational results are presented in Figure 19. These results are similar to those shown in Figures 14 through 17 but are for specific roughness data and additionally show the effect of operating the pipeline at reduced head pressures to achieve power savings.

A presentation of detailed economics is deferred at present because of the lack of information on the amount of polymer required as well as data on delivered polymer costs. Economics have been considered in choosing test concentration levels but their discussion is beyond the scope of this report.

## L. SUMMARY

(1) Data obtained from SwRI flow tests have been plotted on Prandtl-Karman coordinates according to the model of Virk. The linear variations which were observed are as predicted by Virk. Important features of Virk's model are (A) a single critical wall shear stress for each polymer, (B) an increase in the slope of the characteristic curve on Prandtl-Karman coordinates as the polymer concentration increases, and (C) a cutoff wall shear stress related to the wall roughness. Single critical wall shear stresses were not observed in the data.

(2) The data obtained at SwRI have been reduced to yield critical wall shear stresses and characteristic (P-K) slope increments for each of the polymer types. Where obtained, concentration dependencies indicate that some shear degredation occurred in the pump used in the SwRI tests.

(3) A model of Newtonian flow in the West Hackberry brine pipeline and diffuser section has been developed and implemented. This model satisfactorily describes flow in the pipeline and, when applied to determine the overall pipe roughness, yields 0.0022 feet.

(4) A model to describe the flow of polymeric drag reducing solutions has been developed and implemented to describe the brine flow in the West Hackberry brine pipeline.

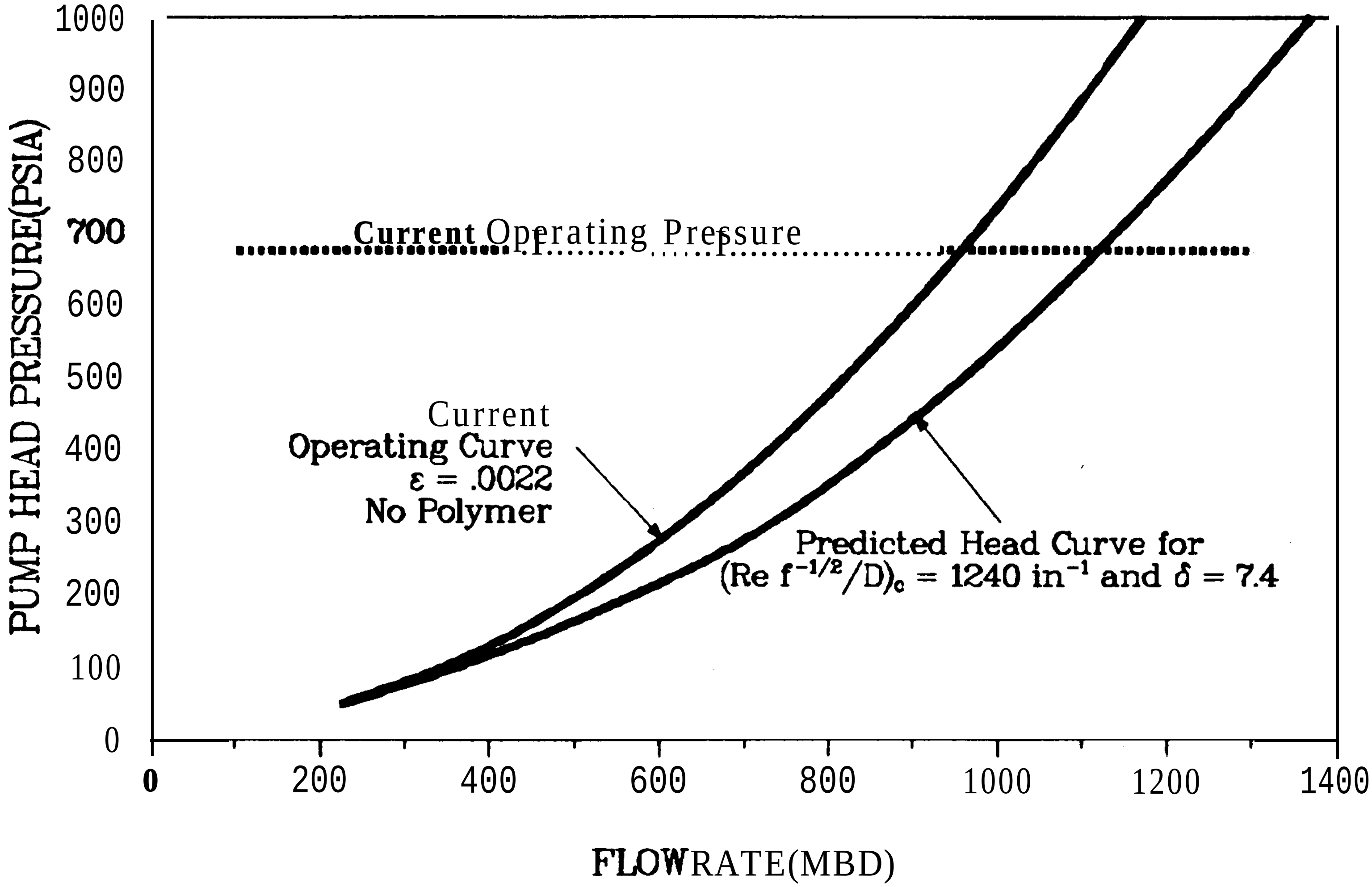


**Figure 19. Predicted West Hackberry brine pipeline performance for a pipe roughness of .0022 ft. Polymer properties are similar to those obtained for material #1.**

(5) A test plan to determine parametric values which predict the performance drag reducing agents has been formulated.

(6) The application of preliminary test data and the polymeric solution flow model indicate that 20 percent improvement in flow may reasonably be obtained with drag reducing agents.

## M. REFERENCES


1. Berman, N. S., "Drag Reduction by Polymers," Ann. Rev. Fluid **Mech.,** 10, 47 (1978).

2. Boicourt, G. W., Shear Degredation of Polyethylene Oxide, Ph.D. Dissertation, Wayne State University, 1975.

3. Bowles, E. G., Jr., "Brine/Polymer Mixture Drag Reduction Characteristics," Final Report on Contract 47-2033, **SwRI** Project **No.** 06-7664, Oct. 1983.

4. Burger, E. D., L. G. Chorn, T. K. Perkins, "Studies of Drag Reduction Conducted over a Broad Range of Pipeline Conditions When Flowing Prudhoe Bay Crude Oil," J. of Rheology, 24, 603 **(1980).**

5. Darby, R., H. D. Chang, "Generalized Correlation for Friction **Loss in** Drag Reducing Polymer Solutions," **A.I.Ch.E.J.,** 30, 274 (1984).

6. Hoyt, **J.** W., "Polymer Drag Reduction - A Literature Review 1975-6," Second International Conference **On** Drag Reduction, Aug. 31, 1977.

7. Hoyt, J.W., "The Effect of Additives on Fluid Friction*', Trans. **ASME,** J. of Basic Engineering, June, 258 **(1972).**

8. Savins, J. G., F. A. Seyer, "Drag Reduction Scale-up Criteria," Phys. Fluids, 20, **S78** (1977).

9. **Sellin,** R. H. J., **M.** Ollis, "Effect of Pipe Diameter on Polymer Drag Reduction,** Ind. Eng. Chem. Prod. Res. Dev., 22, 445 (1983).

10. Virk, P.S., "Drag Reduction Fundamentals", **A.I.Ch.E.J.,** 21, **625(1975)**

11. Virk, P.S., "Drag Reduction in Rough Pipes," J. Fluid **Mech.,** 45, 225 (1971).

12. Zimm, B.H., "Dynamics of Polymer Molecules in **Dilute** Solutions: Viscoelasticity, Flow Birefringence, and Dielectric Loss," J. Chem. Phys., 24, 269 (1956).

## APPENDIX A

DESCRIPTION OF FLOW RATE - PRESSURE DROP MODEL

A schematic of the West Hackberry pipeline is shown in Figure Al. For this pipeline an energy balance may be written for flow between points 1 and 2,

$$\frac{p_1}{\rho} + z_1 \frac{g}{g_c} + \frac{v_1^2}{2g_c\alpha} = \frac{p_2}{\rho} + z_2 \frac{g}{g_c} + \frac{v_2^2}{2g_c\alpha} + \sum F \qquad \text{(A1)}$$

where $z$ is the elevation, a is the weight factor accounting for the velocity profile deviation from plug flow and $\sum F$ is the fluid friction head loss and is defined as $\Delta p/\rho$ due to fluid friction. For flow in the main pipeline $v_1$ and $v_2$ are equivalent so that

$$\sum F = \frac{p_1 - p_2}{\rho} + (z_1 - z_2) \frac{g}{g_c} \qquad \text{(A2)}$$

and from the definition of the friction factor

$$\sum F = \frac{2fv^2L}{g_c D} \qquad \text{(A3)}$$

A method of solving these equations involves first assuming a value for $p_2$ and then calculating $\sum F$. Then $Re\sqrt{f}$ in Equation (1) is determined since

$$Re\sqrt{f} = \frac{D\rho}{\mu}\sqrt{\frac{g_c D \sum F}{2L}} \qquad \text{(A4)}$$

From Equation (1) then f is determined and v is finally determined from Equation (A3). This average velocity times the cross-sectional area gives the volumetric flow rate. Since $p_2$ was assumed to begin this calculation, its value must be varied until flow in the main pipeline matches flow in the diffuser.

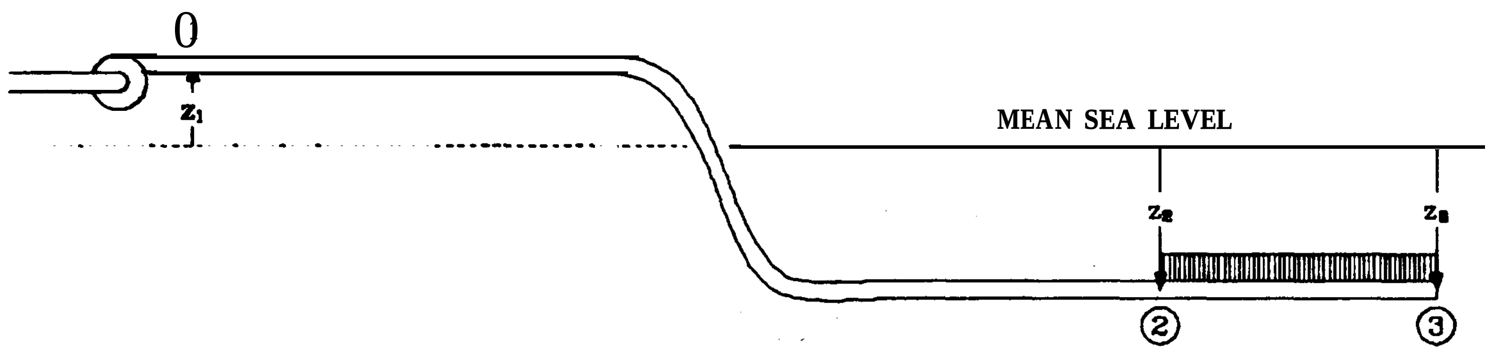


**Figure** A1. Schematic of West Hackberry brine pipeline.
**Total** length: **26.4 miles** + 3240 **feet** in diffuser
Reference positions are **as** indicated.

The flow in the diffuser section is depicted by the schematic in Figure A2 because of pressure matching condition, $p_A = p_2$. The energy balance applied for any one of the nozzles, but written for nozzle A, is

$$\frac{p_A - p_e}{\rho} + (z_1 - z_e)\frac{g}{g_c} = \sum F \tag{A5}$$

where $p_e$ is the pressure in the nozzle throat at the exit condition and

$$p_e = p_{ATM} + (z_{MSL} - z_e)\frac{g}{g_c}\rho_{sw} - \frac{\rho v^2}{2g_c\alpha} \tag{A6}$$

where $p_{ATM}$ is the atmospheric pressure, $z_{MSL}$ is the elevation of mean sea level, and $\rho_{sw}$ is the sea water density. Since $p_e$ will decrease as the flow increases, it must be limited to values greater than the vapor pressure of the brine. Flow rates greater than this amount will not occur, and the nozzle at this point is considered choked. At the higher flow rates attainable with drag reducing agents in the West Hackberry pipeline, this type of choking is actually observed in the most upstream nozzles of the diffuser section.

Equations (1), (A3), (A5), and (A6) must then be solved simultaneously to yield the flow through the first nozzle, A. The total flow through the main pipeline is then reduced by the amount which flowed out of nozzle A.

For the diffuser section between points A and B, the pressure drop needs to be determined for the total pipe flow rate less that which flowed out of one nozzle. In this case there is no elevation change in the diffuser section so that

$$\sum F = \frac{p_A - p_B}{\rho} \tag{A7}$$

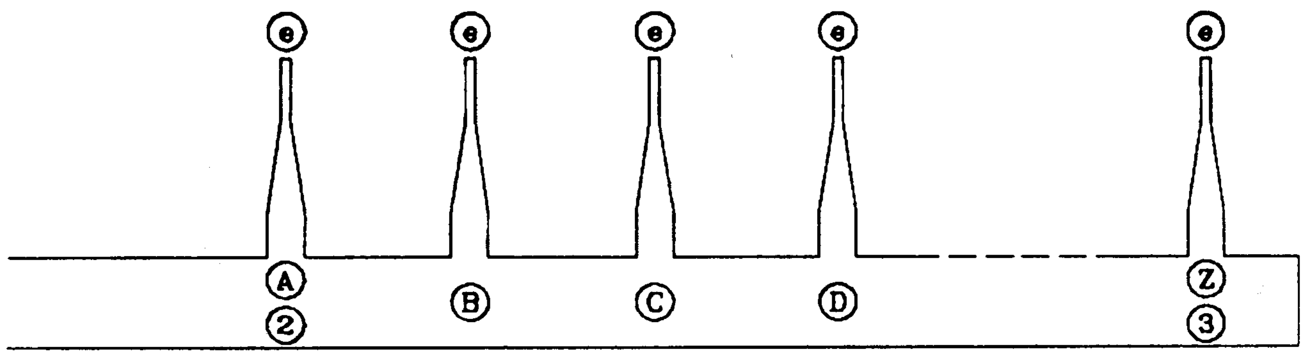


**Figure AZ. Schematic of** diffuser section.
**Reference positions are as** indicated.

Equation (1), (A3), and (A7) are then solved simultaneously for hp. Thus, $p_B$ is determined and the second nozzle flow may be calculated by the same method as was used for nozzle A. This solution method is then repeated to obtain all nozzle flows, the sum of which must equal the pipe flow, $p_2$ (or $p_A$) is then adjusted until this is so. In this manner flow through the complete pipeline system is determined as a function of the head pressure, $p_1$, the pipe roughness and dimensions, and the fluid properties.

Distribution

US Department of Energy (10)
Strategic Petroleum Reserve PMO
Attn: E. E. Chapple, PR-632 (8)
TCDS, L., Smith (2)
900 Commerce Road East
New Orleans, LA 70123

US Department of Energy (2)
Strategic Petroleum Reserve
Attn: D. Johnson
D. Smith
1000 Independence Ave., SW
Washington, DC 20585

US Department of Energy (1)
Oak Ridge Operations Office
Attn: P. Brewington, Jr.
P.O. Box E
Oak Ridge, TN 37831

Aerospace Corporation (2)
Attn: K. Henrie
R. Merkle
800 Commerce Road West, Suite 300
New Orleans, LA 70123

Walk-Haydel & Associates (1)
Attn: R. Haney
600 Carondelet
New Orleans, LA 70112

POSSI (2)
Attn: K. Mills
820 S. Clearview Pkwy
New Orleans, LA 70123

Southwest Research Institute (1)
Attn: E. B. Bowles, Jr.
6220 Culebra Rd.
San Antonio, TX 78284

| | |
|---|---|
| 1512 | J. C. Cummings |
| 1521 | R. D. Krieg |
| 1542 | B. M. Butcher |
| 1821 | N. E. Brown |
| 6200 | V. L. Dugan |
| 6250 | B. W. Marshall |
| 6257 | J. K. Linn (10) |
| 6257 | J. K. Linn |
| 6257 | T. E. Hinkebein (10) |
| 8024 | M. A. Pound |
| 3141 | C. M. Ostrander |
| 3151 | W. L. Garner |
| 3151-4 | C. H. Dalin (28) For Unlimited Distribution |